THIN LENS BETA SPECTROMETER

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by

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Major, United States Army

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

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IN

PHYSICS

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PREFACE

With the rapid growth in the knowledge and understanding of the nature of fundamental atomic particles and forces, a means of measuring the energies of particles became imperative. Since the electron was one of the first atomic particles identified and understood, it was natural that an instrument would be devised to measure its energy. Many types of beta-ray spectrometers have been constructed. Approximately in 1950, one such beta spectrometer was constructed for the U. S. Naval Radiological Defense Laboratories at Hunter's Point, San Francisco, California. Due to an inadequate cooling system on the magnet coil, among other reasons, the instrument was later abandoned and was acquired by the U. S. Naval Postgraduate School. As part of this thesis project, the writer devised and installed a new cooling system on the magnet coil, within the limitations that an increase in the over-all diameter of the coil was to be held to a minimum.

It is the aim of this paper to describe several general types of beta spectrometers, to discuss the theory of the thin-lens type, and to provide operational data regarding the remodeled beta spectrometer.

The writer wishes to thank Professor Edmund A. Milne of the U. S. Naval Postgraduate School for his assistance, encouragement and cooperation in the preparation of this paper. The writer also wishes to thank: his wife, Marga, for her assistance in re-winding the coil; the personnel of the Postgraduate School Machine Shop for their assistance in constructing the new spools for the coil; the personnel of the Postgraduate School Public Works for their assistance in remodeling the

table on which the spectrometer is permanently mounted; and the personnel of the Department of Physics, Postgraduate School for their assistance in procuring the various materials required.

TABLE OF CONTENTS

Item	Title	Page
Chapter I	Introduction	1
Chapter II	Beta-Ray Spectrometers	5
Chapter III	Thin-Lens Beta-Ray Spectrometer	26
Bibliography	. . . . .	54
Appendix I	Data for New Coil	58
Appendix II	Definitions and Notations	59
Appendix III	Fundamental Formulas	64
Appendix IV	Useful References for Further Study of Beta-Ray Spectrometers	66

LIST OF ILLUSTRATIONS

Figure		Page
1.	Flat Type, Magnetic-Field Beta-Ray Spectrometer	10
2.	Helical Type, Magnetic-Field Beta-Ray Spectrometer, Path of Electron	16
3.	Traces of Electron Paths in Axially-Symmetric Magnetic Fields	17
4.	Double Thin-Lens Beta-Ray Spectrometer	21
5.	Magnetic Lens Nuclear Spectrometer	23
6.	Long Lens Spectrometers	24
7.	Thin Lens (Short Lens) Spectrometer	27
8.	General View, Beta Spectrometer, Original Coil (USNPS)	28
9.	Source End, Beta Spectrometer, Original Coil (USNPS)	29
10.	Detector End, Beta Spectrometer, Original Coil (USNPS)	30
11.	Beta Spectrometer, New Coil Form Details, Isometric (USNPS)	32
12.	Beta Spectrometer, New Coil Form Details, Plan (USNPS)	33
13.	Transferring the Original Coil to the Winding Rack (USNPS)	34
14.	Winding the New Coil (USNPS)	35
15.	Cooling Tubes, New Coil (USNPS)	37
16.	Cooling System, Beta Spectrometer, New Coil (USNPS) . .	38
17.	General View, Beta Spectrometer, New Coil (USNPS) . . .	39
18.	Source End, Beta Spectrometer, New Coil (USNPS)	40

Figure		Page
19.	Detector End, Beta Spectrometer, New Coil (USNPS) . . .	41
20.	Electrical Dimensions, Original Coil, Beta Spectrometer (USNPS)	42
21.	Electrical Dimensions, New Coil, Beta Spectrometer (USNPS)	43
22.	General Assembly, Beta Spectrometer (USNPS)	45
23.	Comparison of Thin Lens Beta Spectrometers	46
24.	Magnetic Field Distribution, Thin Lens Beta Spectrometer	47
25.	Electron Trajectory, Thin Lens Beta Spectrometer . . .	50

CHAPTER I

INTRODUCTION

For more than a half-century electric and magnetic fields have been used in determining the velocities and the ratio of charge to mass of fundamental particles and ions. In 1897, J. J. Thompson proved the existence of the electron and measured the ratio of its charge to mass [62]. A few years later the same individual used perpendicular electric and magnetic fields to construct the first mass spectroscope [30], a device for determining the ratio of the charge to mass of ions.

In 1918, A. J. Dempster published information regarding his mass spectrograph [15] which employed a uniform magnetic field and was able, with an ion beam of homogeneous velocity, to separate ions with different values of ratio of charge to mass by deflecting the ions through an angle of 180°. Soon thereafter, in 1919, F. N. Aston published information on a mass spectrometer which used a combination of electric and magnetic fields [2].

Although the problems encountered and the techniques used in mass spectroscopy are similar to those of beta-ray spectroscopy, the basic problem is easier in the latter because the ratio of charge to mass of a beta particle is constant when the velocity is constant.

The term "beta" radiation or particle was used as far back as 1899 when F. O. Giesel showed that the radiation from a radium source contained at least two components [21]. The first component, which appeared to be undeflected by a magnetic field, was called "alpha" radiation: the deflected part was called the "beta" component. In 1903, with a stronger

magnetic field, E. Rutherford showed that the "alpha" portion of the radiation could be resolved further into two components [49]. The first of these new components was deflected in a direction opposite to that of the beta rays, and retained the name "alpha" rays. The second of these new components was undeflected in the strongest electric and/or magnetic fields, and became known as "gamma" rays.

The beta rays from radioactive substances have been identified as high-speed electrons ejected from the nuclei of the radioactive atoms. Alpha rays were found to consist of the positively charged nuclei of helium atoms stripped of their outer electrons. Gamma rays consist of high-frequency electromagnetic radiations similar to x-rays [30].

It has been known for a long time that the beta rays emitted by radioactive substances have a continuous distribution in energy. It was also realized that these electrons would be deflected in a magnetic field according to their momenta or mass-velocity (mv) products. This provides a simple method of sorting out the various energies of the spectrum.

One of the first experiments in beta spectroscopy was performed in 1910 by O. von Baeyer and O. Hahn [66]. They passed a beam of beta rays through a uniform magnetic field and thereby obtained a spectrum of beta-rays. The magnetic field deflects the beta-rays in amounts related to the different momenta. Baeyer and Hahn used a photographic plate to detect the "spread" of the spectrum.

Soon afterwards, J. Danysz pointed out that the spread-out beam could be re-focused by using a very simple geometrical property of the circle, e.g., that if a circle is given an infinitesimal rotation around one of its points, the point diametrically opposed is displaced along

a tangent [12, 13, 14]. This principle has been stated in somewhat more detail by H. Bruining [6]:

> If a point source emits electrons with the same energy all at the same angle to the lines of force of a homogeneous magnetic field, the electrons will meet again at a point. The distance from this image point to the point source is proportional to the velocity of the electrons and inversely proportional to the magnetic field. The device acts therefore as a velocity selector.

Thus electrons of a constant momenta gave rise to a very sharp line on a photographic plate placed 180° from the source of electrons; this was the first practical beta-ray spectrograph [30]. E. Rutherford and H. Robinson applied this principle of semicircular focusing, and developed an improved type of beta-ray spectrograph in 1913 [50].

The development of the Geiger-Müller counter about 1928 resulted in its replacing the photographic plate in beta-ray spectrographs, and thus converting these spectrographs to beta-ray spectrometers. The photographic plate is replaced by a narrow exit slit which permits a very small portion of the spectrum to fall on the G-M counter window. The counting rate registered by the counter is proportional to the "intensity" of beta-rays picked up by the slit, and therefore may be considered as a measure of the "density" of the spectrum for a given value of the momentum [42]. By changing the magnetic field and scanning the entire spectrum in small increments, the spectrum can be analyzed.

Among the advantages of the spectrometer over the spectrograph are that it requires a magnetic field over a smaller area, and that the homogeneity of the field may be less perfect since electrons of different momenta will still follow identical trajectories [42]. Once the

apparatus is calibrated, it will give the value of the momentum directly from the measurement of the magnetic field. Another advantage is that, even though corrections must be made for the background and for the thickness of the counter window, the intensity measurements are more exact with a counter than with a photographic plate.

The development of the G-M counter and its adaptation to beta-ray spectrometers spurred the development of several different types of spectrometers. Some of these types will be discussed in Chapter II.

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CHAPTER II

BETA-RAY SPECTROMETERS

1. General Types of Spectrometers.

The large variety of beta-ray spectrometers may be divided into two general classes, electrostatic-field spectrometers and magnetic-field spectrometers; the second class is used to a much greater extent than the first [56]. According to accepted nomenclature, both classes are further sub-divided into types as follows:

A. Electrostatic-field beta-ray spectrometers.

(1) Radial-field focusing type.

(a) Two-dimensional field focusing type.

(b) Three-dimensional field focusing type.

(2) Retarding-field type.

(a) Single retarding field.

(b) Double retarding field.

B. Magnetic-field beta-ray spectrometers.

(1) Flat type.

(a) First-order single-focusing.

(b) Third-order single-focusing.

(c) First-order double-focusing.

(2) Helical type.

(a) Solenoid spectrometer.

(b) Short lens spectrometer.

(c) Long lens spectrometer.

Each of the above types of beta-ray spectrometers will be discussed individually.

2. Electrostatic-field Beta-ray Spectrometers.

The use of electrostatic-field spectrometers is ordinarily confined to the low-energy portion of the beta spectrum because its use with high-energy particles would require extremely high voltages [30]. The use of electrostatic-fields may be desirable in certain types of experiments such as when a secondary electron multiplier is to be used as a particle detector; in this case the proximity of a strong magnetic field might prevent the proper operation of the electron multiplier.

In the radial-field focusing type, the two-dimensional focusing type employs an inverse first-power electrostatic-field between portions of two concentric circular conducting cylinders. In 1929, A. L. Hughes and V. Rojansky found that a cylindrical condenser of this type had a refocusing property for electron orbits provided the orbits satisfied certain conditions [27]. In such a field, the orbits of electrons of the same initial velocity tend to refocus at a point 127° from the starting point, as contrasted with the case of a uniform magnetic field where refocusing occurs at 180°. K. T. Bainbridge and E. B. Jordan describe a mass spectrometer which employs an electrostatic analyzer of the above-described type [3].

The three-dimensional field focusing type of beta-ray spectrometer was first suggested by F. N. Aston in 1919 [2] and the theory of the focusing of charged particles by means of such a spherical condenser was worked out and demonstrated by E. M. Purcell in 1938 [43]. Since the spherical condenser has a much larger aperture, it possesses some advantages over the cylindrical-condenser type of spectrometer, but it is far more difficult to construct.

The retarding-field type of electrostatic spectrometer possesses an inherent advantage over the magnetic deflection types. Whereas the magnetic methods give only the distribution curve of electrons emitted in one specified direction, the retarding-electric field measures all emitted electrons [6].

In 1950, D. R. Hamilton and L. Gross published details of their electrostatic beta-ray spectrometer which employed a single retarding field to investigate the low energy portion (0-30 kilovolts) of the spectrum of sulfur 35 [24]. In this device, electrons move radially outward against a spherically symmetric retarding electric field, and the current due to these electrons is measured by an electrometer. For a given retarding field voltage E_o, only beta particles with energies greater than E_o can overcome the retarding field and reach the collector plate to be recorded by the electrometer. With a sufficiently large retarding field voltage no electrons will surmount the field, and hence no current is registered by the electrometer. As the retarding field is reduced, more and more electrons are allowed to reach the collector plate, and consequently the electrometer will indicate more and more current. Since the current is a measure of the relative number of electrons able to surmount the retarding field, the spectrum measured is the integral of the ordinary spectrum, and hence must be differentiated in order to obtain the ordinary spectrum. The single retarding field spectrometer possesses the advantage of having a large solid angle of collection (2π), but it also has the inherent disadvantages of any device that must measure very small currents by means of an electrometer.

In a double retarding field electrostatic spectrometer, the operation is considerably different from that of a single retarding field. In the double retarding field apparatus, the first potential field, of E_1 volts, rejects all electrons of energy greater than E_1 volts. The second retarding field, of $E_1 - \Delta E_1$ volts, rejects all electrons of energies less than this potential. Thus, in general, only beta particles of an energy spread of ΔE_1 volts are recorded by the apparatus. In 1955, H. R. Johnston published details on a beta-ray spectrometer which employs a double retarding field, and which uses a secondary electron multiplier as a detector [30]. The nominal beta-energy range of the machine as constructed is from one to 50 kev. It is about equal in transmission and somewhat superior in resolution to the flat type of magnetic field spectrometer. It is especially useful in the lower energy ranges that cannot be measured with magnetic spectrometers.

3. Magnetic-field Beta-ray Spectrometers.

Magnetic-field beta-ray spectrometers make use of a magnetic field, either homogeneous or inhomogeneous, to focus a beam of beta-rays onto a detector. The two major sub-classifications of magnetic-field spectrometers are the "flat" type and the "helical" type; these classifications arise from the manner in which the magnetic field is employed [56].

When the magnetic field is oriented so that the lines of force are principally perpendicular to the electron paths, the electrons will describe circles in a homogeneous field, and will be focused in one plane only, hence the name "flat" type. In ordinary optics the flat type of spectrometer would correspond to a cylindrical lens.

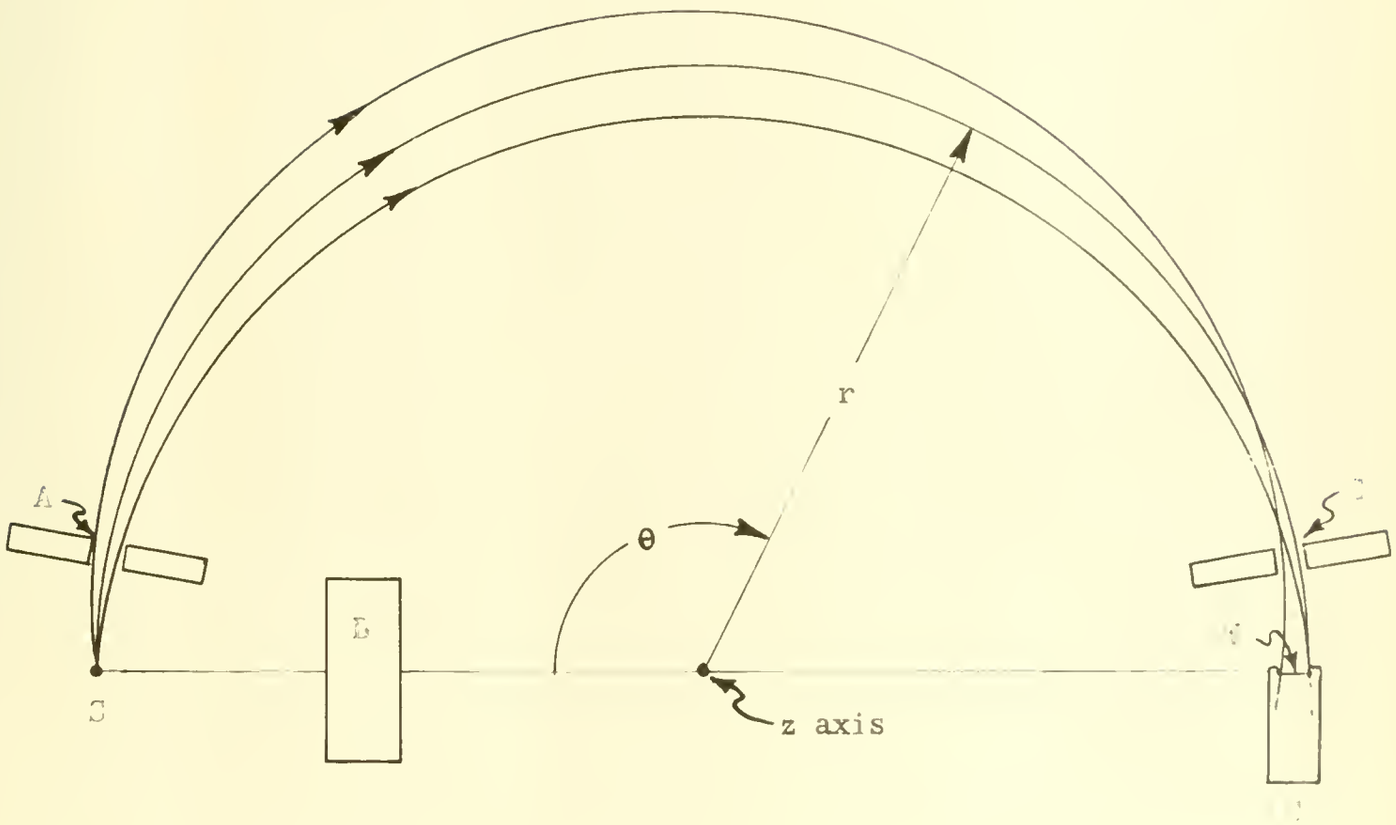
When the magnetic field is oriented so that the lines of force are mainly parallel to the electron paths, the electrons will describe helical paths and will be space focused, hence the name "helical" type. In optics the helical type would correspond to a spherical lens.

Both flat and helical types of spectrometers have the same essential parts: a source of electrons, an entrance slit, a magnet, an exit slit or window, and a counter. In addition there is the necessary supplemental equipment for production of the vacuum and the magnetic field, and the electrical control equipment. In the spectrometer itself, there is some sort of lead shield interposed between the source and the counter to prevent gamma-rays from the source from reaching the counter. There are also several other baffles, variously placed throughout the spectrometer; the function of these is not to define the electron beam but to prevent secondary and scattered beta-rays and gamma-rays from reaching the counter [42]. Since a magnetic lens focuses both positive and negative electrons to the same point, a helicoidal-shaped baffle is required if it is necessary to distinguish between the two types.

4. Flat Type Magnetic-field Spectrometers.

Figure 1, page 10, shows the general principles of the flat type magnetic-field beta-ray spectrometer. Since all electron optical systems possess aberrations, it is not surprising that the flat type of spectrometer has its share. It will be noted that the semicircular focusing of electrons of a given momentum in a uniform magnetic field is only approximate for two reasons [42]:

A - Entrance slit
B - Lead baffle
C - Counter
D - Exit slit
S - Source
W - Window



Source and counter are in plane z = 0.

z axis is perpendicular to plane of drawing.

Figure 1. [illegible]

a. For an electron which leaves the source at an angle α with plane $z = 0$, the component of its momentum as projected on the $z = 0$ plane will be a function of $\cos\alpha$, hence its projected path at the exit slit will lie somewhat closer to the z axis than the path of an electron which leaves the source at an angle of $\alpha = 0$. The horizontal displacement of the first electron is proportional to the square of the initial angle α.

b. All of the circles of a given radius which pass through the source do not meet the exit slit at the same point: the displacements of these circles are of an order of magnitude equal to the square of the angular aperture of the beam in the plane $z = 0$.

Thus semi-circular focusing is called "first-order" focusing because the rays will meet on the same line only to the extent that powers of the angular apertures higher than the first power are neglected.

For the purpose of discussing the different types of flat spectrometers, the cylindrical coordinates r, θ, and z will be used as indicated in Figure 1, page 10. The axes are oriented in such a way that the central electron trajectory lies in the horizontal plane $z = 0$, and the source in the plane $\theta = 0$. The magnetic field is assumed to be independent of θ and symmetrical with respect to the median plane $z = 0$. The vertical component of the field is H_z and the radial component H_r: H_θ is always zero. The trajectory of the electron will depend on the initial position and momentum of the electron, and also on the form of the magnetic field. Variations in the form of H_z result in changes in the kind and the degree of focusing, and lead to the classification of flat spectrometers into the three groups:

(1) First-order single-focusing.

(2) Third-order single-focusing.

(3) First-order double-focusing.

Each group will be discussed separately.

5. First-order Single-focusing Flat-type Spectrometer.

The first-order single-focusing spectrometer was the first practical type developed [12, 13, 14]. It uses a uniform magnetic field whose lines of force are in the z direction, that is, perpendicular to the electron trajectory. As a consequence, H_z is constant and H_r is always zero. Since there is no restoring force in the z direction, there will be no focusing in that direction. On the other hand, in the r direction there is first-order focusing in the diametral plane through the source, with the focus impact point in the plane $\theta = \pi$. For the cylindrical coordinate equations of the electron trajectory, see the articles by F. B. Shull and D. M. Dennison [53, 54]. If the homogeneous magnetic field is replaced by an inhomogeneous field, the 180° first-order single-focusing spectrometer will be modified into one of the other types.

6. Third-order Single-focusing Flat-type Spectrometer.

If the magnetic field is so shaped that it will correct the third-order aberration due to the horizontal aperture of the beam without correcting the aberration due to the vertical aperture of the beam, third-order horizontal focusing is obtained. This permits a very divergent beam in the horizontal plane z = 0, without impairing too greatly the resolving power of the spectrometer. There is no focusing in the z direction, but

a very good focusing in the r direction for $\theta = \pi$. For the cylindrical coordinate equations of the electron trajectories see references [4] and [5].

In 1933, C. D. Bock presented information on his study of the shape of a magnetic field which would accomplish third-order focusing [5]. In 1948, F. M. Beiduck and E. J. Konopinski presented further information on such a study [4]. The first spectrometer to utilize such a shaped field appears to have been constructed by J. M. Langer and C. S. Cook in about 1948 [36]. A short time later J. A. Bruner and F. R. Scott constructed a spectrometer patterned after that of Langer and Cook, but of a smaller size [7]. This second instrument is a medium-size, high resolution, 180° flat type magnetic focusing beta-ray spectrometer with a principal orbit radius of 15 centimeters. A radially inhomogeneous field provides essentially perfect focusing of electrons leaving the source within a 33° angle.

7. First-order Double-focusing Flat-type Spectrometer.

In the double-focusing spectrometer, the magnetic field is slightly decreasing toward the exterior of the orbit. Electrons coming from any point of the source describe an arc and come to focus at an impact point in the plane $\theta = \sqrt{2}\,\pi = 254°\ 33'$ for certain values of a field parameter. The main difference between this type of focusing and semi-circular focusing is that in this type two electrons can emanate from the same point of the source with different angles of inclination to horizontal plane $z = 0$, and both electrons will come to focus at the same point on the image line; thus there is first-order focusing not only in the r

direction but also simultaneously in the z direction, i.e., double focusing. The chief advantage of this type of spectrometer over that of the semi-circular focusing type is that the resolving power is increased for the same luminosity [42]. For the cylindrical coordinate equations of the electron trajectories see references [53, 54].

At least three spectrometers of the double-focusing type had been built prior to 1950; the first by N. Svartholm and K. Siegbahn [61], the second by F. B. Shull [52], and the third by F. Kurie, J. Osoba, and L. Slack [35]. All three of these have the same general design, with the source and detector located $\sqrt{2}\,\pi = 254°\ 33'$ apart, and the entrance slit located on the electron trajectories half-way between the source and detector. The designs differ in the use of different values for a field parameter β [42].

Subsequent modifications have been designed and additional analyses published regarding the double-focusing type of spectrometer. D. L. Judd [31] and E. S. Rosenblum [48] have both suggested that the source and counter be placed outside the magnetic field to give a better arrangement for the use of particle accelerators as sources. Rosenblum analyzed the focusing characteristics of a magnetic spectrometer having an annular magnetic field which varies approximately with $1/\sqrt{r}$, thus permitting axial as well as radial focusing of particles of a given energy. By considering the field angle and source location as independently variable, his analysis provided for a more flexible instrument.

8. Helical Type Magnetic-field Spectrometers.

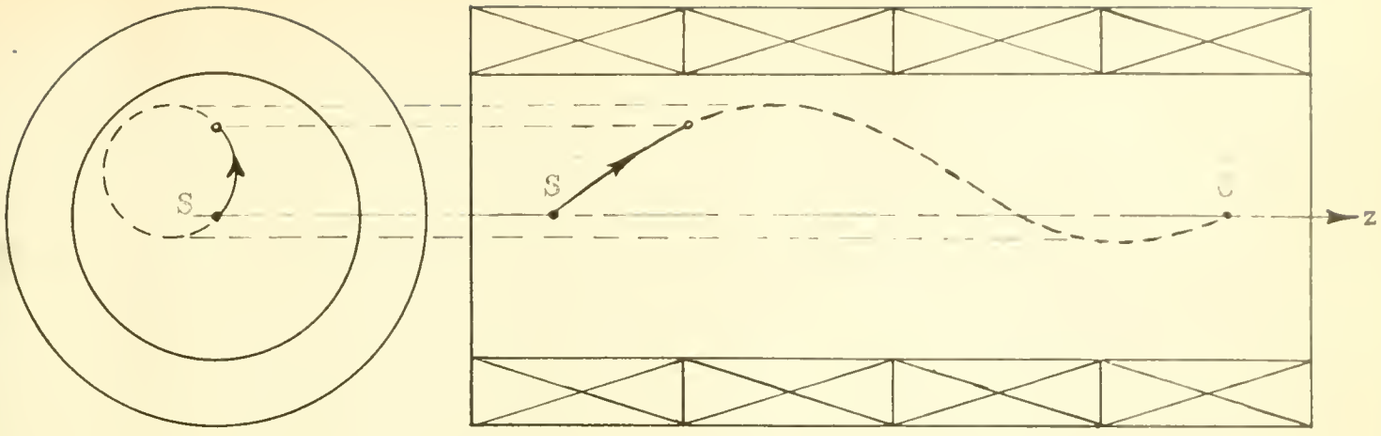
An axially symmetric magnetic field acts like a convergent lens and

will focus electrons coming from a source on the axis of the field. This focusing action of short and long coils has been known for a long time: H. Busch [8, 9] however, was the first to point out the close analogy between ordinary light and electron optics when dealing with these magnetic lenses [56]. He showed that the ordinary lens formula $1/u + 1/v = 1/f$ could be applied also to electron lenses, and was able to calculate the focal distance f for a short lens. Figure 2, page 16 shows a typical helical path of an electron in a uniform magnetic field beta-ray spectrometer in which the lines of force are parallel to the electron paths. Since the apparatus is symmetrical about the axis of this field, the path of the electron can be "flattened" for study by graphing its perpendicular distance from the axis as ordinate versus its longitudinal position as abscissa; this will give the optical "trace" of the path as indicated in Figure 2, page 16. The shape of the trace will vary with the shape of the magnetic field. Figure 3, page 17, indicates the effect of variations in the shape of an axially symmetric field. Note that the trace in a uniform field is sinusoidal in shape.

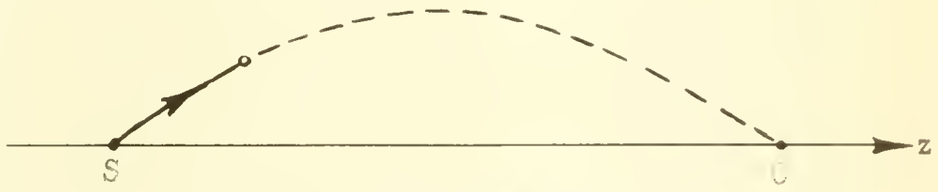
The distinction between types of helical spectrometers is due primarily to variations in the type of magnetic lens. In all types the magnetic field is axially symmetric.

a. If the magnetic field is uniform, the field is produced by a long solenoid: this gives rise to the name "solenoid spectrometer." The source and counter are located within the magnetic field.

b. If the magnetic field is non-uniform and is confined to a small region between the source and detector, the resulting spectrometer

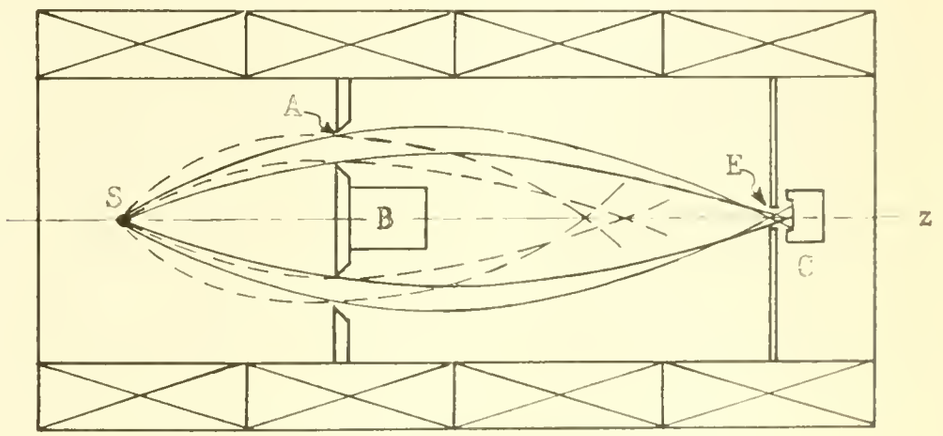


Path of Single Electron



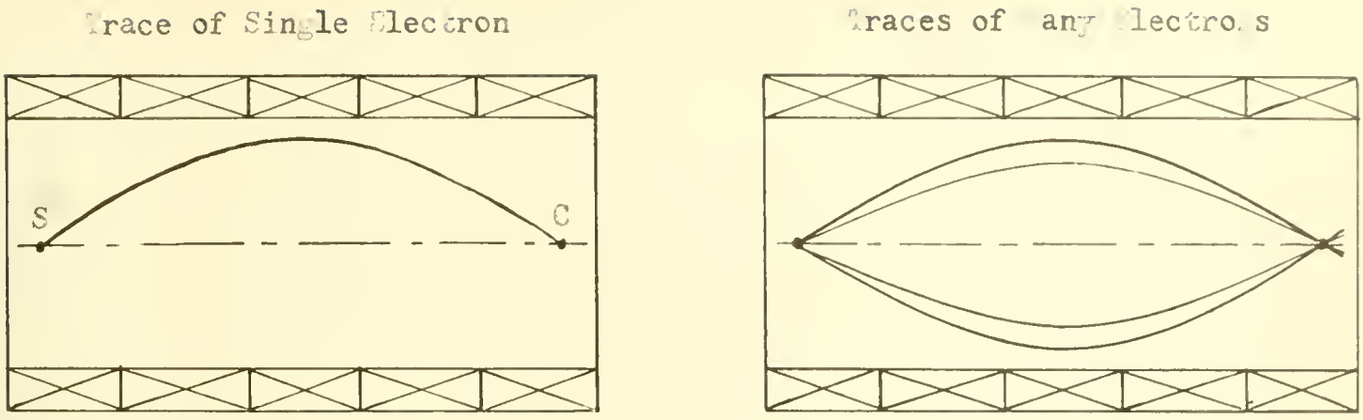
Trace of Single Electron

A - Entrance slit
B - Lead baffle
C - Counter
E - Exit slit
S - Source

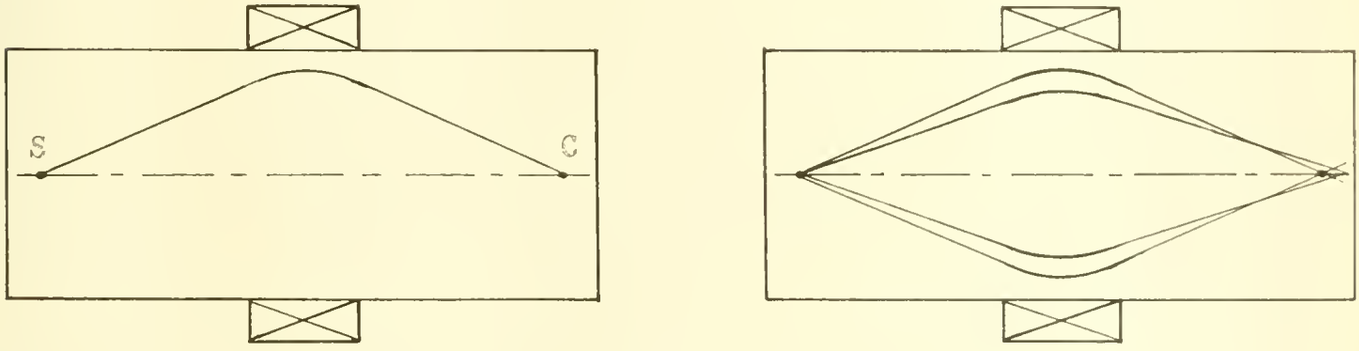


Pattern Formed by Many Electrons

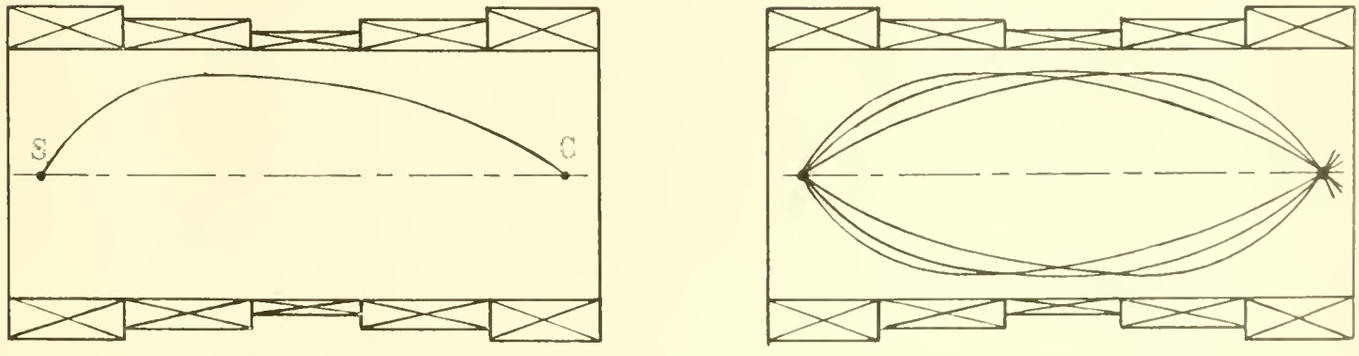
Figure 2. [illegible]



(a) Uniform Field (Solenoid Spectrometer)



(b) Non-Uniform Field (Short Lens Spectrometer)



(c) Non-Uniform Field (Long Lens Spectrometer)

Figure 3. TRACES OF ELECTRON PATHS IN AXIALLY-SYMMETRIC MAGNETIC FIELDS

is called a "short-lens" type. The magnetic field is produced by means of a relatively flat coil, usually without iron. Both the source and detector are located outside of the field.

c. If the magnetic field is non-uniform and extends throughout the paths of the electrons, the spectrometer is called a "long-lens" type. The field is produced by several coils aligned along the same axis, and may or may not have an iron core.

9. Solenoid Spectrometer (Helical Type).

Figure 3 (a), page 17, shows the relation of the magnetic coil to the vacuum tube of a solenoid type instrument. The solenoid spectrometer with a point source is the type of spectrometer for which the theory is most advanced, because the traces of the electron paths are of a simple sinusoidal shape which offers the possibility of rigorous analytical calculation [42]. Other advantages of this type are the easier adjustment and the reduced sensitivity to external magnetic perturbations; the chief disadvantage is the necessity for use of large dimensions and considerable electric power if high energy beta-rays are to be analyzed.

The first helical spectrometer was of the solenoid type and was constructed by R. A. R. Tricker in 1924 [63]. Another spectrometer of this type was built in 1941 by C. M. Witcher [67]. Still others have been publicized as follows: 1942 by E. Haggstrom [23], 1946 by Swami Jnanananda [29], and 1950 by L. Feldman and C. S. Wu [19,20].

An interesting modification of the solenoid spectrometer was proposed by P. Hubert in 1950 [26]. He suggested that the separate entrance and

exit slits be replaced by a unique baffle placed at the ring image: this baffle would limit the beta-ray beam internally. Two or more other baffles would limit the beam externally. He claimed that the resolving power of the instrument would be increased by a factor of approximately 4/3 with the same peak transmission.

At least two instruments have been built which incorporate the ring-focus shutters suggested by Hubert. In 1952 F. Schmidt [51] described his spectrometer which employs a flat, oil-cooled, supplementary coil on each end of the uniform field coils to compensate for the end effects of the field. In the same year, J. DuMond, et al [18] published information on another interesting design in which particular care was taken to form as uniform a field as possible in order to be able to use the proton resonance method for field measurements and to adjust the spectrometer for high resolution.

10. Short Lens Spectrometer (Helical Type).

Figure 3 (b), page 17, shows the relation of the magnetic coil to the vacuum tube of a short-lens type of instrument. Due to the nature of the magnet coil, a short-lens spectrometer is also known as a "thin-lens" spectrometer; these terms will be used interchangeably in this paper.

In a short lens spectrometer both the source and counter are outside of the area where the magnetic field is of appreciable strength; as a result, the traces of the electrons consist of two straight lines (one before the field and one after the field), joined by a sharply bent curve (in the magnetic field); see Figure 3 (b), page 17. In general these traces cannot be calculated analytically but must be determined by numerical computation according to techniques described in

books on electron optics, such as that by V. K. Zworykin et al [69]. Because of the difficulty of calculating the complex traces of the electrons in this type of instrument not much has been published concerning short lens spectrometers.

A simplified theory of the short lens spectrometer with circular exit window was published by M. Deutsch, L. Elliott, and R. Evans in 1944 [17]: that theory will be discussed in Chapter III of this paper.

The first short lens spectrometer was built by G. Klemperer [34, 42] in about 1935. Many others have been built or designed subsequently: in 1940 by V. E. Crosslett [10]; in 1942 by K. Siegbahn [55]: in 1944 by M. Deutsch et al [17]; in 1947 by L. C. Miller and L. F. Curtiss [39]: in 1947 by W. Rall and R. G. Williamson [46]; in 1949 by W. Hornyak, T. Lauritsen and V. Rasmussen [25]; in 1949 by E. Jensen, L. Laslett and W. Pratt [28]; and in 1950 by N. F. Verster [65]. Also in 1950 one was built for the U. S. Naval Radiological Defense Laboratories: this one will be discussed in Chapter III.

An interesting modification of the thin-lens spectrometer was developed by C. M. Van Atta et al in 1950 [64]. They describe a double thin-lens beta-ray spectrometer patterned after a design first given by E. A. Quade and D. Halliday in 1948 [44], which, in turn, was a modification of the original thin-lens design of Deutsch and his co-workers [17]. Figure 4, page 21, shows the general arrangement of the magnetic coils in this spectrometer.

A more recent thin-lens type of spectrometer was constructed in 1953 by L. A. Kiley et al [33] for the measurement of beta-ray and gamma-ray

C - Counter
S - Source

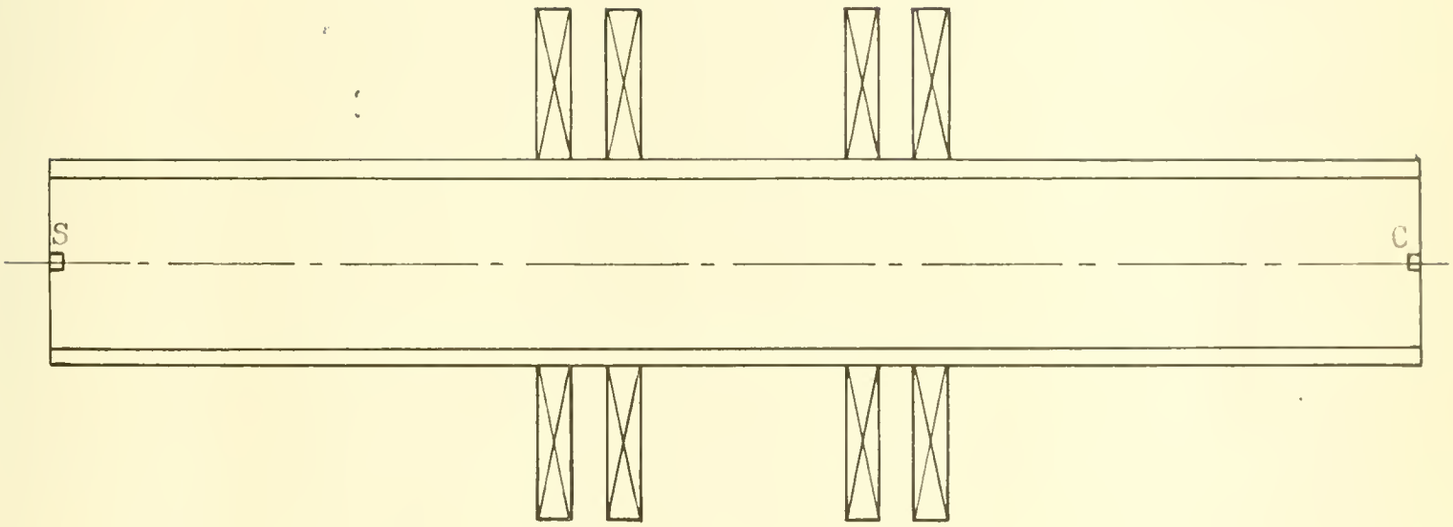


Figure 4. DOUBLE T II-LE S BETA-RAY SPECTROMETER

energies up to about 6 Mev. Diverse operating conditions are attained by means of exchangeable baffle systems which can be designed to accommodate either wide emission angles and large transmission, or reduced emission angles and better resolution. The spectrometer design centers around a brass tube of 9 3/4 inches inside diameter which serves as the vacuum chamber. The magnetic lens consists of 28 layers of number eight insulated copper wire wound around the tube, 115 turns per layer: cooling tubes are inserted between the brass tube and innermost layer of wire, and between each seven layers of wire. Figure 5, page 23, shows the general details of this spectrometer.

11. Long Lens Spectrometer (Helical Type).

Figure 3 (c), page 17, shows the relation of the magnetic coil to the vacuum tube of a long lens type of instrument. In a long lens spectrometer both the source and counter are located in the strong part of the magnetic field which renders them relatively inaccessible.

The development of this type of spectrometer resulted from attempts to reduce the spherical aberration of lens spectrometers by suitable distribution of the magnetic field. Elimination of the spherical aberration requires a concave-shaped magnetic field [42].

One method of producing a concave field is by means of a closed cylindrical magnet. The first such instrument was devised by K. Siegbahn in 1946 [57]. Figure 6 (a), page 24, shows the general arrangements of his spectrometer, which consists of a cylindrical iron tube closed at the ends by iron disks: the magnetic coils are inside the tube.

All dimensions are in centimeters.

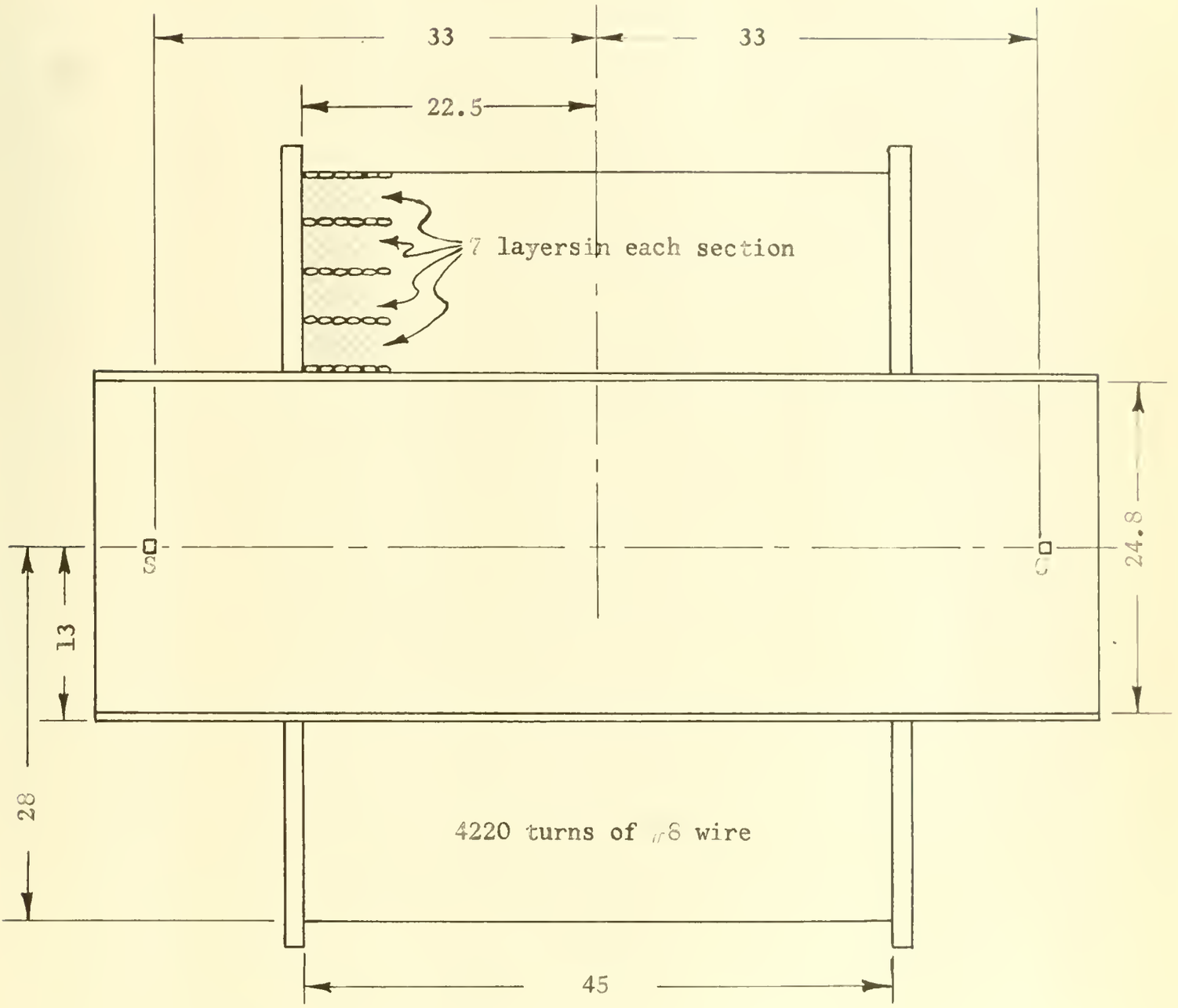
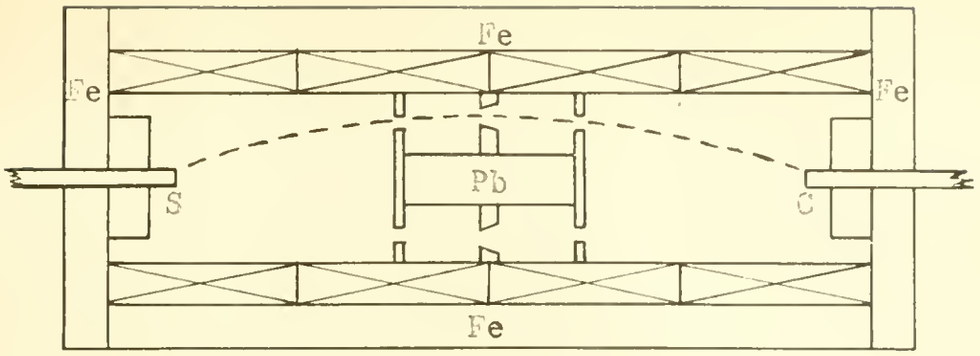
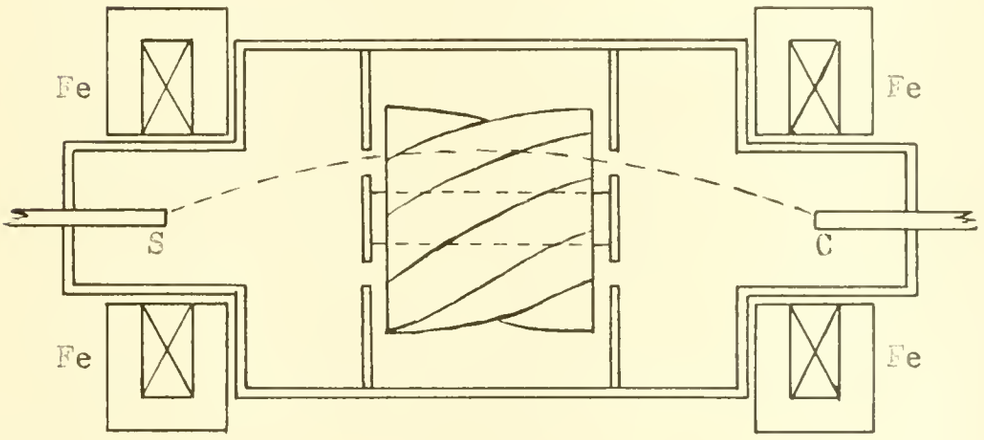


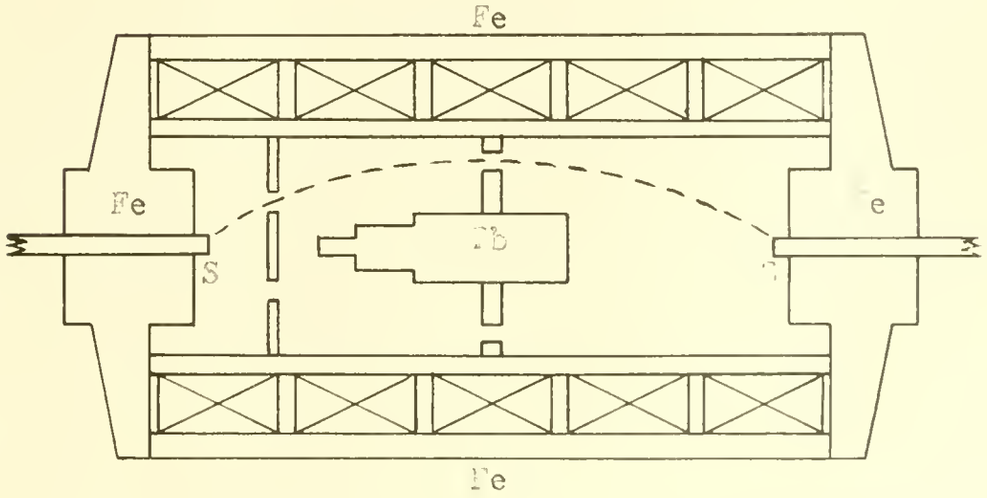
Figure 5. MAGNETIC LENS FOCUSING SPECTROMETER



(a) Long Lens Spectrometer of Siegbahn



(b) Long Lens Spectrometer of Agnew and Anderson



(c) Long Lens Spectrometer of Slätis and Siegbahn

Figure 6. LONG LENS SPECTROMETERS

A second method of producing a concave field is by use of two equal flat coils placed some distance apart on the same axis. This method was applied by T. Lauritsen and R. F. Christy in 1948 [37], and by H. M. Agnew and H. L. Anderson in 1949 [1]. Figure 6 (b), page 24, shows the general arrangements of the spectrometer of Agnew and Anderson. Other long lens spectrometers have been developed and built in 1944 by K. Siegbahn and A. Johansson [58]; in 1948 by W. Zunti [68]: in 1949 by H. Richardson [47]; in 1954 by R. Nichols and E. Jensen [40]: in 1954 by H. Daniel and W. Bothe [11]; and in 1954 by H. de Waard [16].

An interesting variation of the long lens spectrometer was developed by H. Slätis and K. Siegbahn in 1949 [60]. The magnet of this spectrometer is of the closed type and produces a U-shaped field which causes the paths of the electrons to form an intermediate ring image midway between the source and detector; the electrons re-focus again at the detector. Figure 6 (c), page 24, shows the general arrangements of this spectrometer. The ring focus in the central plane permits the use of a ring aperture at that location [59]; this aperture transmits rays of particularly low spherical aberration while eliminating the rays which would contribute to a loss in resolving power. The point focus permits the use of a small detection area and results in a low count due to scattered radiation. The magnetic yoke which aids in forming the U-shaped field also shields the spectrometer from external fields [41].

CHAPTER III

THIN-LENS BETA-RAY SPECTROMETER

1. General Introduction.

The characteristics of thin-lens (short-lens) beta-ray spectrometers have already been discussed in general terms in Chapter II; Figure 7, page 27, gives the main features of such an instrument. This chapter of the paper will be devoted primarily to a discussion of the thin-lens beta-ray spectrometer located at the United States Naval Postgraduate School.

2. The USNPGS Spectrometer, as Received.

The USNPGS spectrometer arrived in a disassembled condition except for part of the vacuum system, the main tube, the thin-lens magnet coil and the unserviceable cooling system. After the remainder of the vacuum system was removed, the spectrometer appeared as shown in Figure 8, page 28. Figure 9, page 29, shows the source end of the spectrometer, while Figure 10, page 30, shows the detector end of the spectrometer. In all three of these photographs one can see the cooling system, which consists of tubing soldered circumferentially on the flat sides of the coil, and the system of valves and connecting tubes. Note that some of the tubes are missing between the valves and coil. The writer's project consisted of building a new coil with an adequate cooling system as an integral part of the coil.

3. Rebuilding the Magnet Coil.

The original coil consisted of five concentric aluminum spools wound with number 14 American Wire Gage copper wire with approximately

A - Entrance slit
B - Lead baffle
C - Counter
D - Coil
E - Exit slit
S - Source
W - Counter window (acts as exit slit if E is absent)

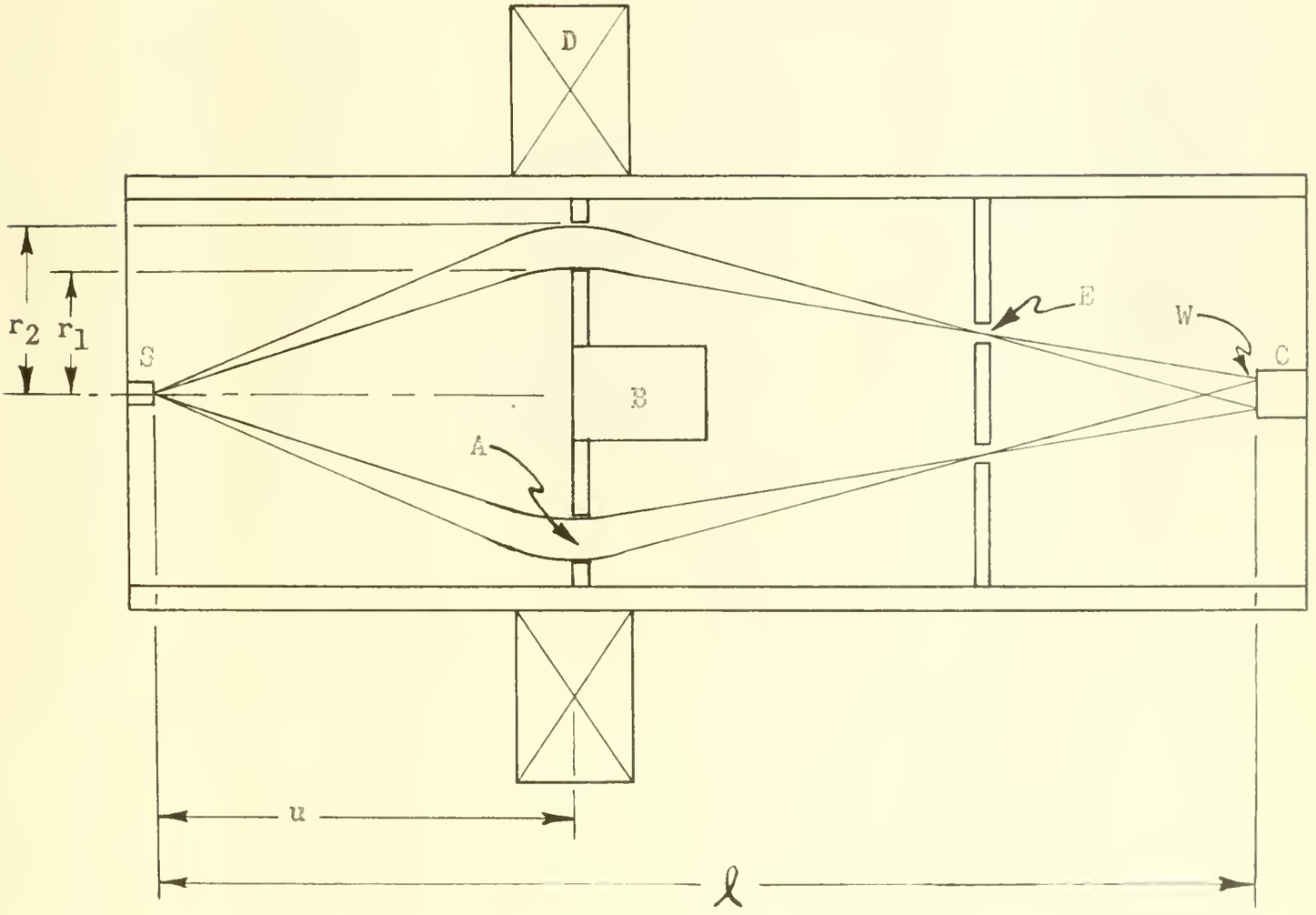


Figure 7. [illegible]

Figure 9. SOURCE END, BETA SPECTROMETER, [illegible]

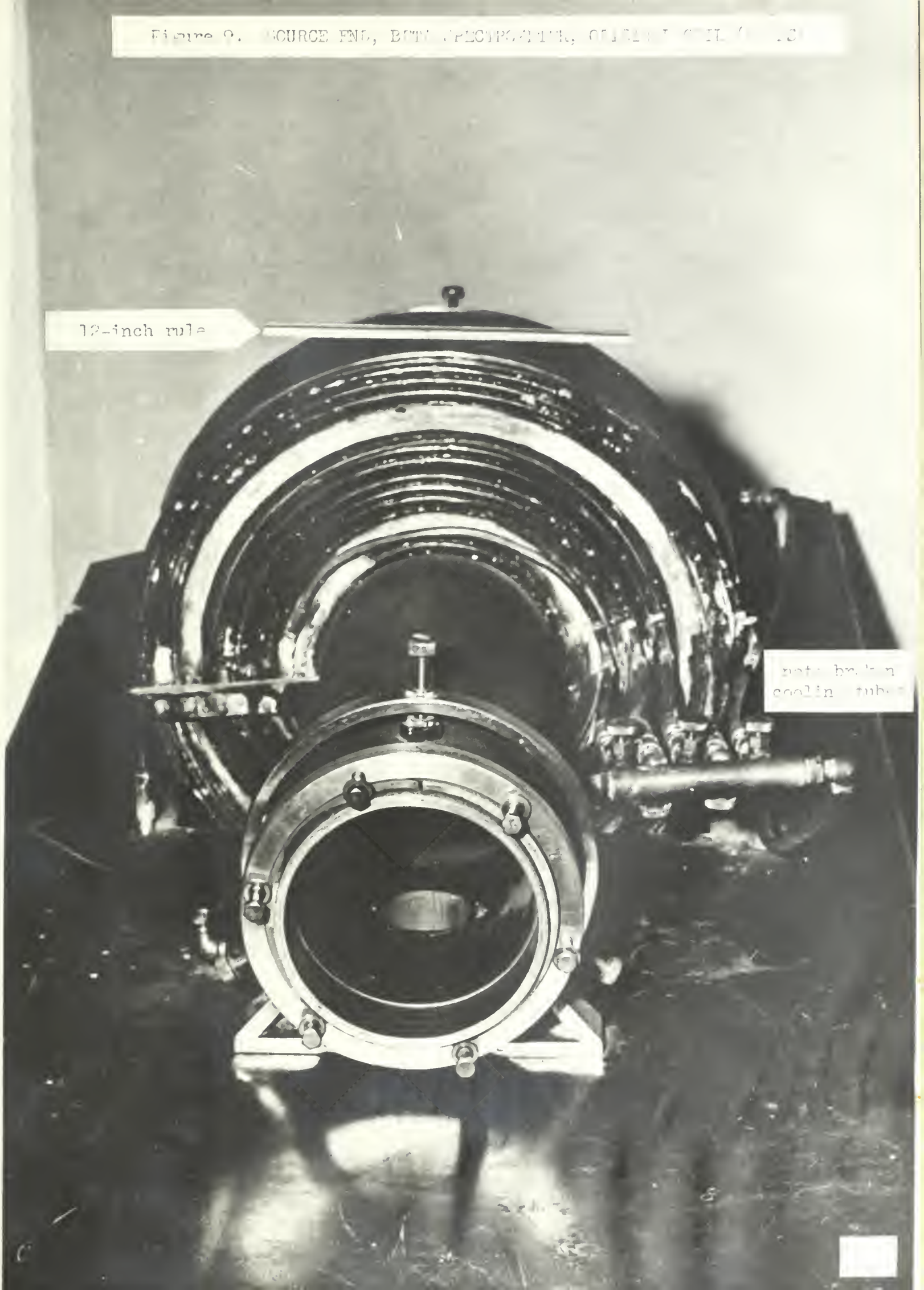
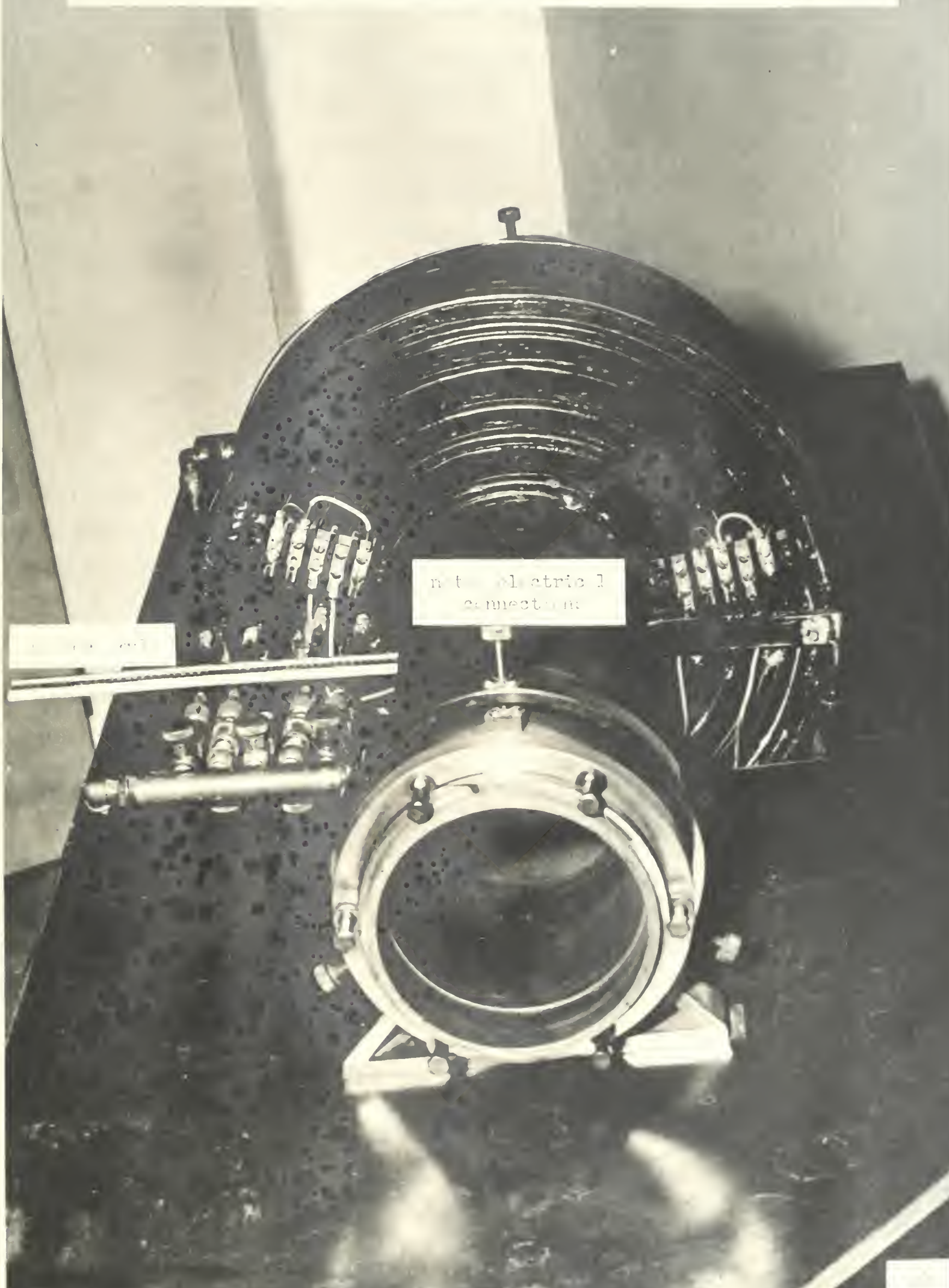


Figure 10. DETECTOR TUBE, BETA SPECTROMETER, ORIGINAL COIL (USNPC)

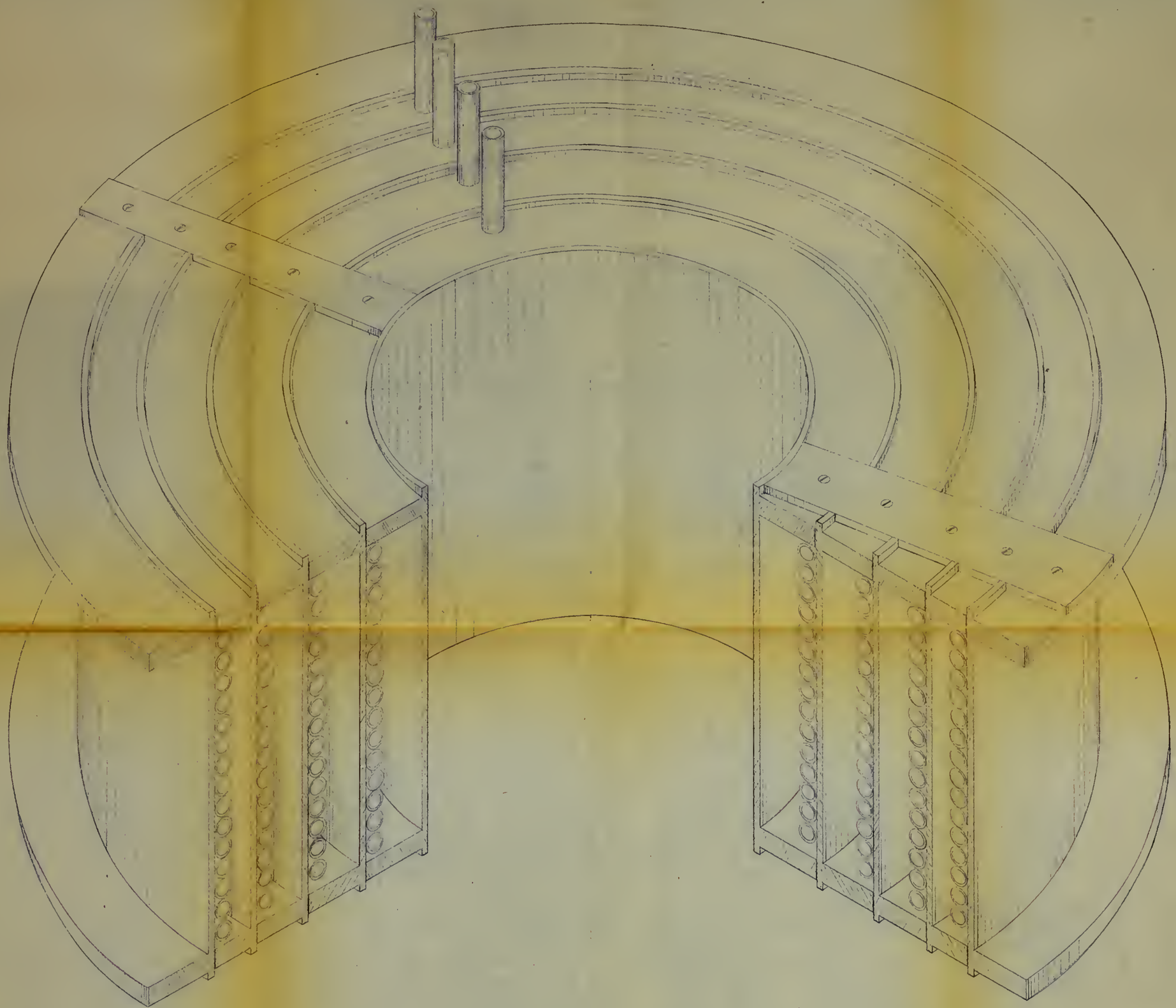


100 turns per layer and 100 usable layers, or 10,000 usable turns. The axial thickness of the coil windings was 6.25 inches.

Based on the dimensions of the original coil, the writer designed a new set of five concentric brass spools of same axial thickness, but with diameters increased a minimum amount to incorporate 1/4-inch OD copper tubing as the outer layer of each spool. The tubing is to serve as conductor for the cooling water. Figure 11, page 32, shows an isometric section of the new coil, while Figure 12, page 33, shows a detailed plan of the new coil.

Since the original coil weighed about 650 pounds, it was necessary to transfer it to a special rack so that the original wiring could be removed and utilized in the new coil. Figure 13, page 34, shows the original coil being transferred to the re-wind rack.

Winding of the new coil presented a difficult mechanical problem. Although fine wire may be wound in high-speed machine operations in the range of 10,000 RPM, the winding of heavy wire (#5 to #24 American Wire Gage) must be done at a low speed; guiding of the wire in the latter case may be by hand or by extra-heavy mechanism [45]. Since this project involved a one-time operation with #14 wire, and the mechanical equipment was not available, guiding was done by hand, with an adjustable static guide to provide some assistance. Based on the total time required for installing a layer of 100 turns, the fastest average speed of winding for a single layer was about five turns per minute. Figure 14, page 35, shows the new coil during the winding process.



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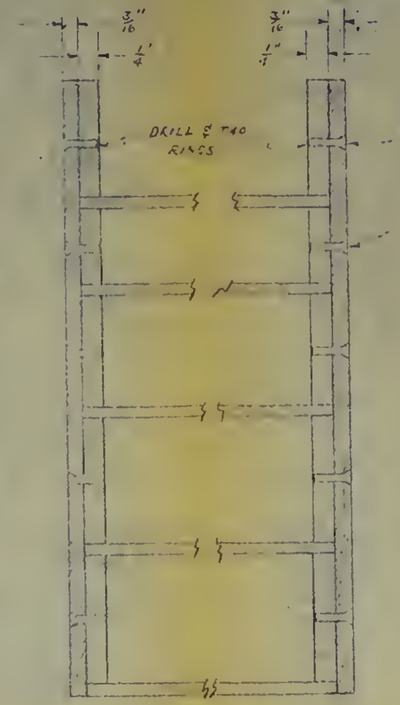
MONTEREY, CALIFORNIA

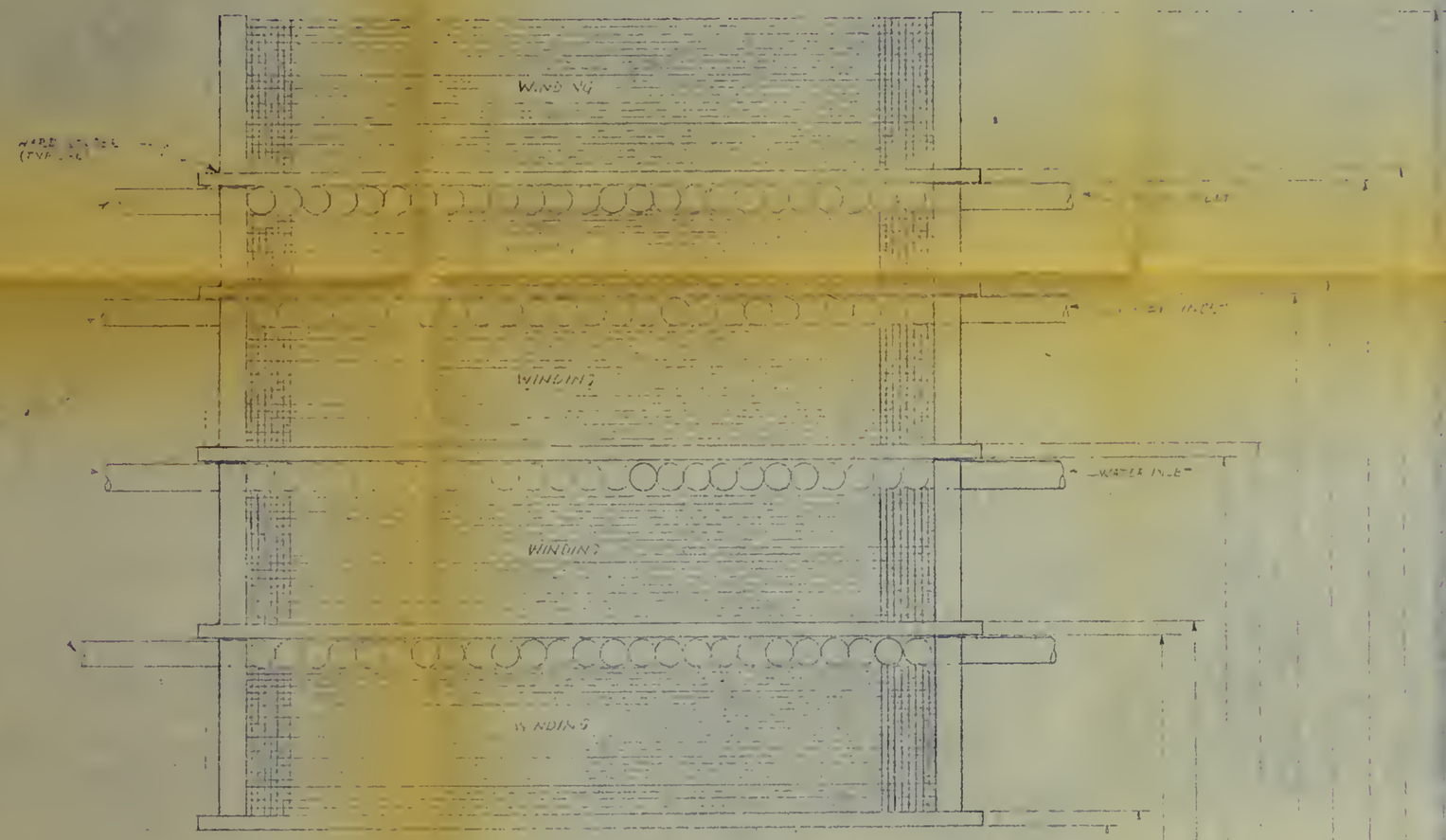
BETA SPECTROMETER COIL FORM DETAILS

DRAWN BY	FEB 6, 1956	APPROVED
J.O HUTTON	SCALE 3/4" = 1" APPROX	FJR



10-32 BRASS COUNTERSUNK
SCREWS

SECT B-B
SCALE 3/4" = 1"



SECT A-A
FULL SCALE

I.D. 7⅞ ±0.010"
O.D. 8 ±0.005"
I.D. 11.355 ±0.005"
O.D. 11.405 ±0.005"
I.D. 14.300 ±0.005"
O.D. 14.350 ±0.005"
I.D. 17.250 ±0.005"
O.D. 17.500 ±0.005"
I.D. 19.750 ±0.005"
O.D. 20.000 ±0.005"
I.D. 22.250 ±0.010"

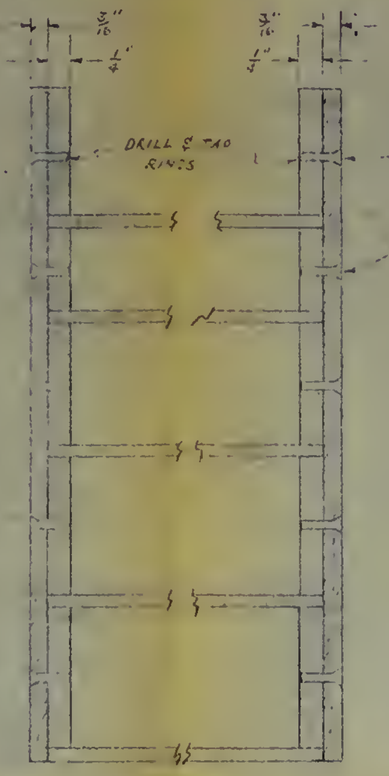
NOTES:

1. RINGS & CYLINDERS TO BE GLASS
2. MACHINE GROOVES SQUARE BETWEEN ASSEMBLIES

ASSEMBLY E
ASSEMBLY D
ASSEMBLY C
ASSEMBLY B
ASSEMBLY A

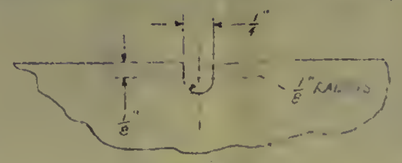
6½" = 6½

SECT A-A
SCALE: 3/8" = 1"

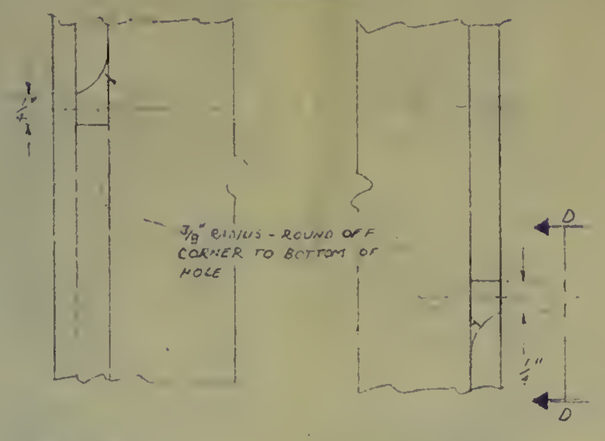


10-32 BRASS COUNTERSUNK SCREWS

SECT B-B
SCALE 3/4" = 1"



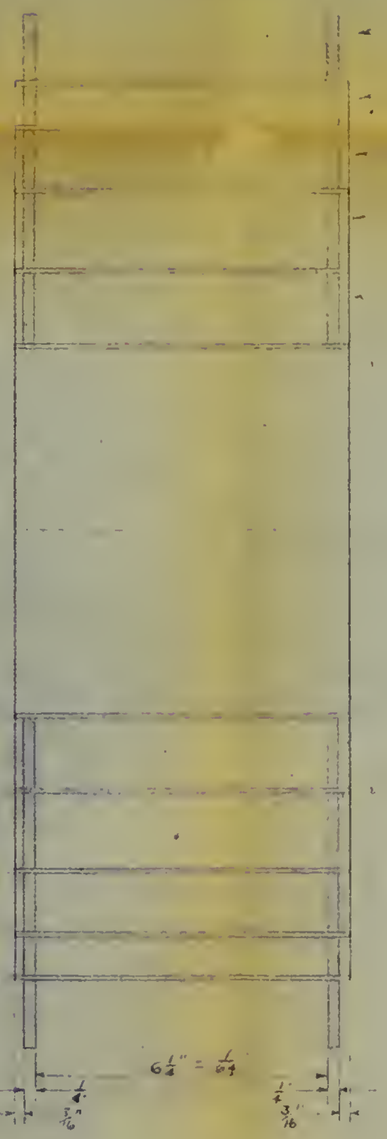
SECT D-D



SECT C-C

SECT E-E

FULL SCALE



SECT A-A
SCALE: 5/8" = 1"

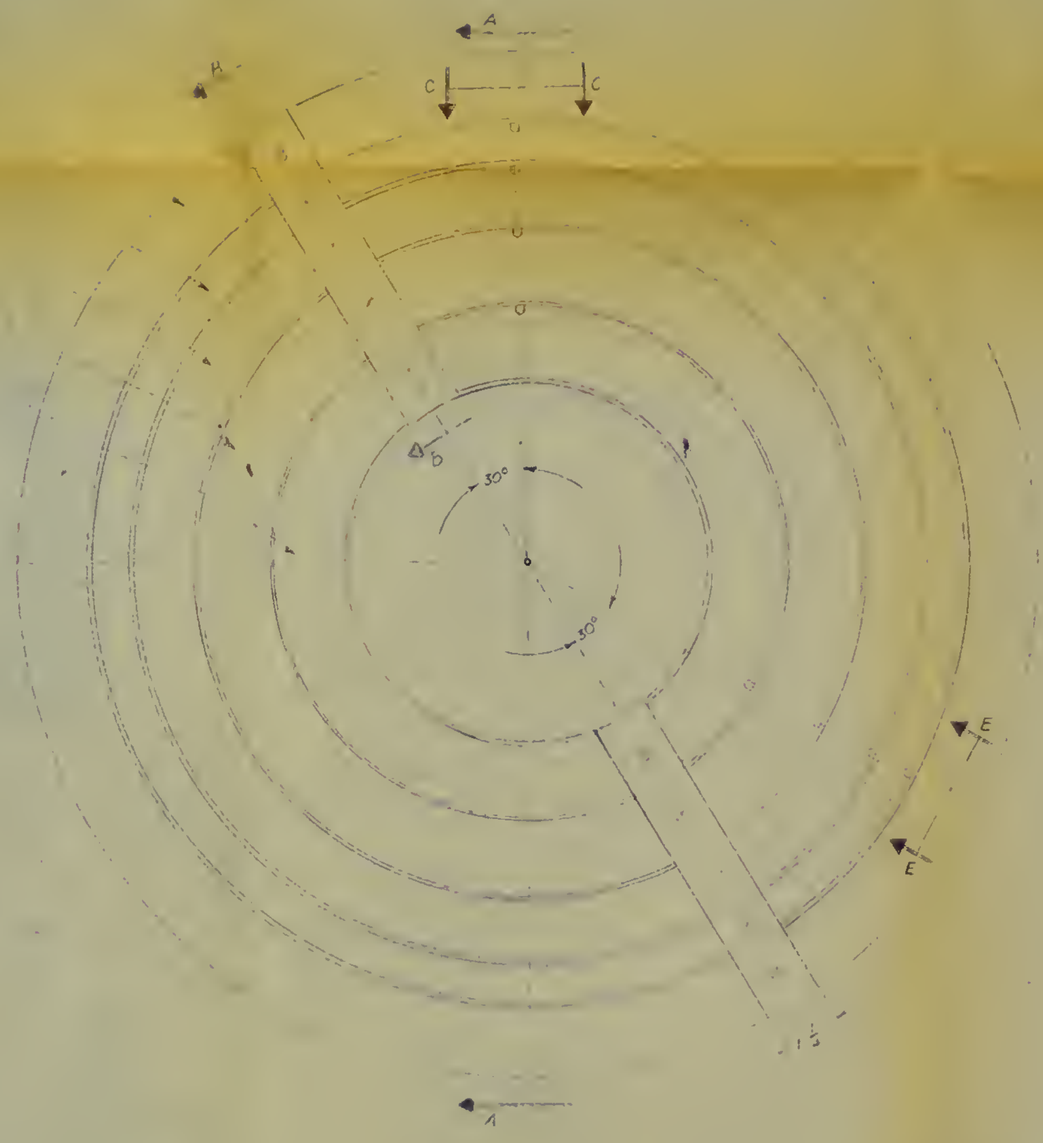
ASSEMBLY E

ASSEMBLY D

ASSEMBLY C

ASSEMBLY B

ASSEMBLY A



SCALE: 5/8" = 1"

O.D. 17.500 ± 0.005"
I.D. 13.750 ± 0.005"
O.D. 26.000 ± 0.005"
I.D. 22.250 ± 0.010"

U.S. NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

BETA SPECTROMETER COIL FORM DETAILS

DRAWN BY	JAN. 22, 1956	APPROVED
[illegible]	SCALES AS NOTED	[illegible]

Figure [illegible] TRANSFERRING THE ORIGINAL COIL TO THE WINDING RACK (USNPS)

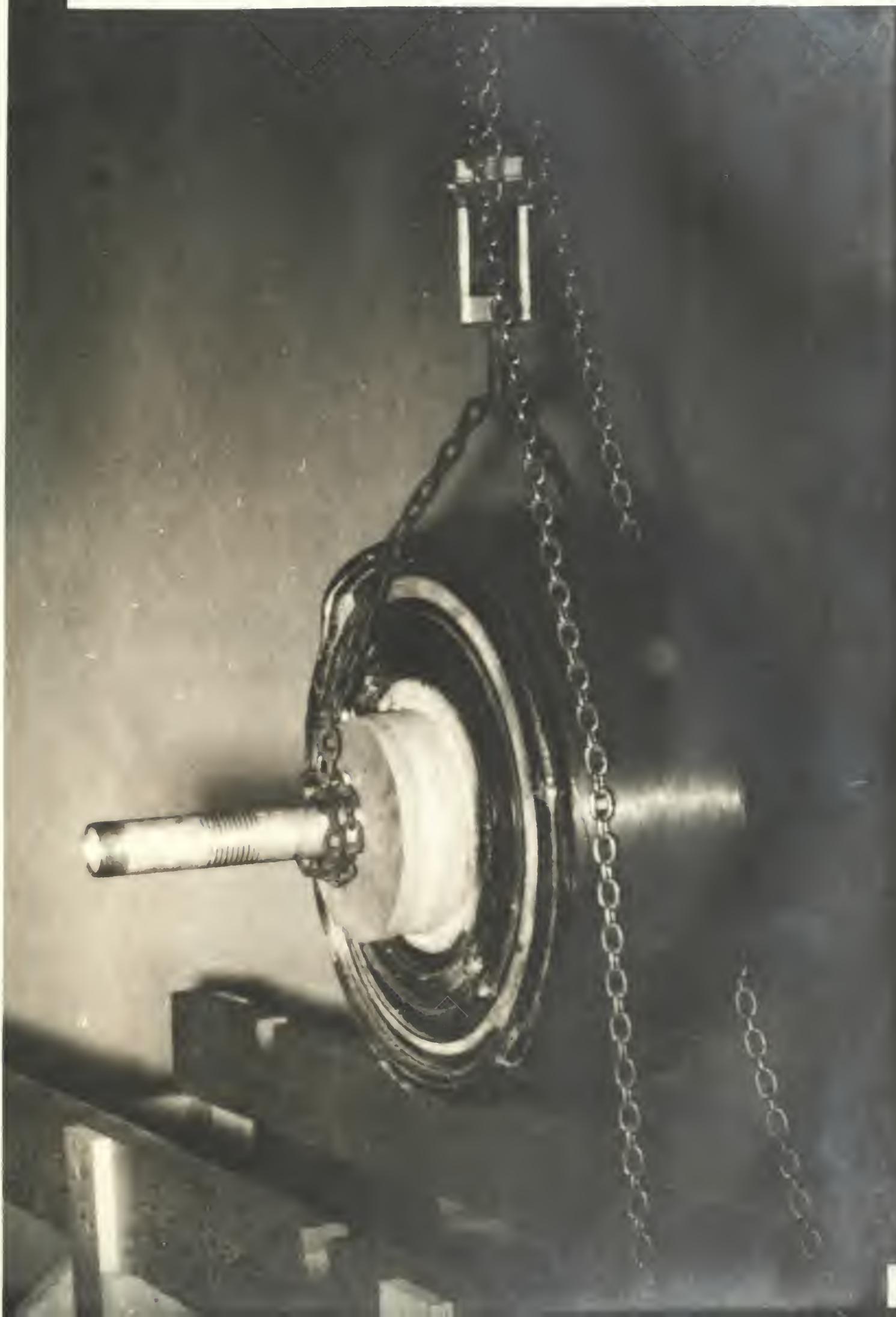


Figure 14. WINDING THE NEW COIL (USNPS)

Figure 15, page 37, shows the cooling tubes of the second spool (counting outward from the central axis). The tubes were insulated electrically from the outside layer of the winding by air-dried varnish and a single thickness of fish-paper.

Figure 16, page 38, shows the valve system and the other external features of the cooling system on the new coil after its final installation. Figure 17, page 39, shows a general view of the USNPS spectrometer with the new coil installed. Figure 18, page 40, and Figure 19, page 41, show the new coil as installed, looking from the source end and from the detector end respectively.

4. Electrical Dimensions of the Coil.

Plans supplied with the USNPS beta spectrometer were lacking in detail regarding the exact electrical dimensions of the original coil. The only information shown was the resistance of the winding on each spool. From that information and other dimensional factors, the data for the original coil were deduced as shown in Figure 20, page 42. Due to the increased diameter of the spools in the new coil, the electrical dimensions are entirely different and are as shown in Figure 21, page 43. Appendix I provides a summary of useful data pertaining to the new magnetic coil.

5. Magnetic Field of the Coil.

No data were available for the original coil to indicate the shape or strength of the magnetic field. Since the electrical control system for the spectrometer has not yet been set up, determination of the

Figure 15. COOLING TUBES, NEW COIL (U[illegible])

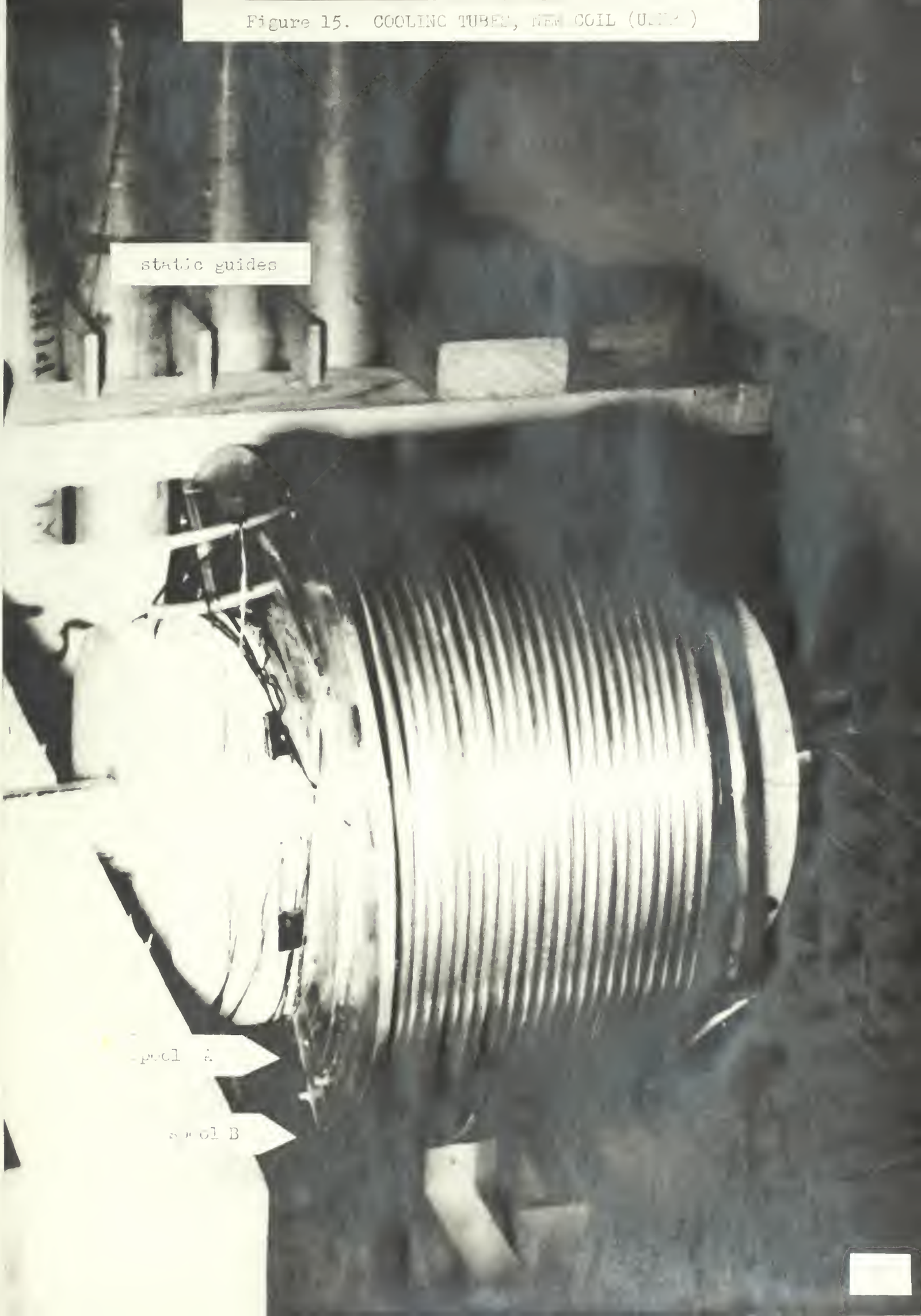
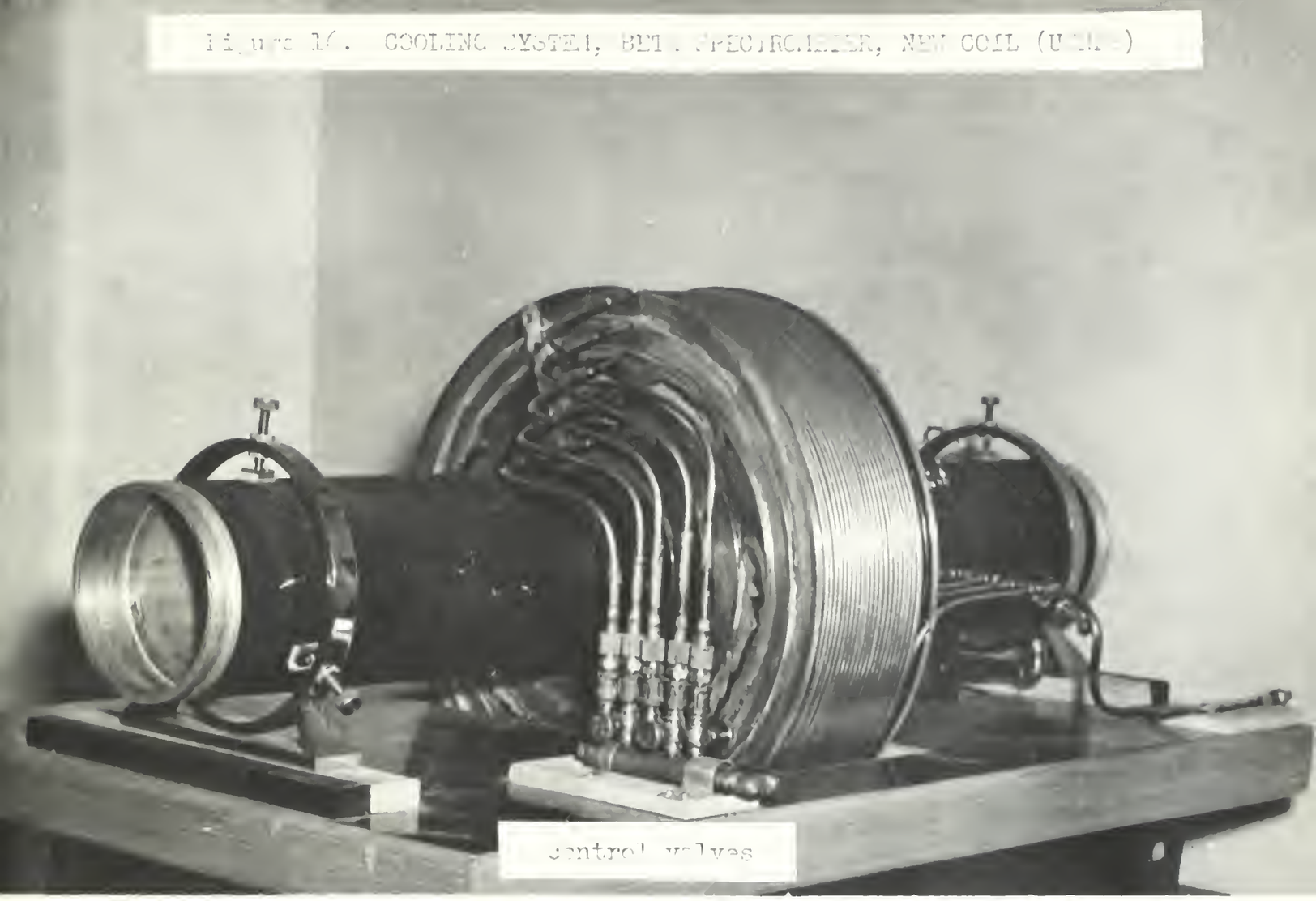
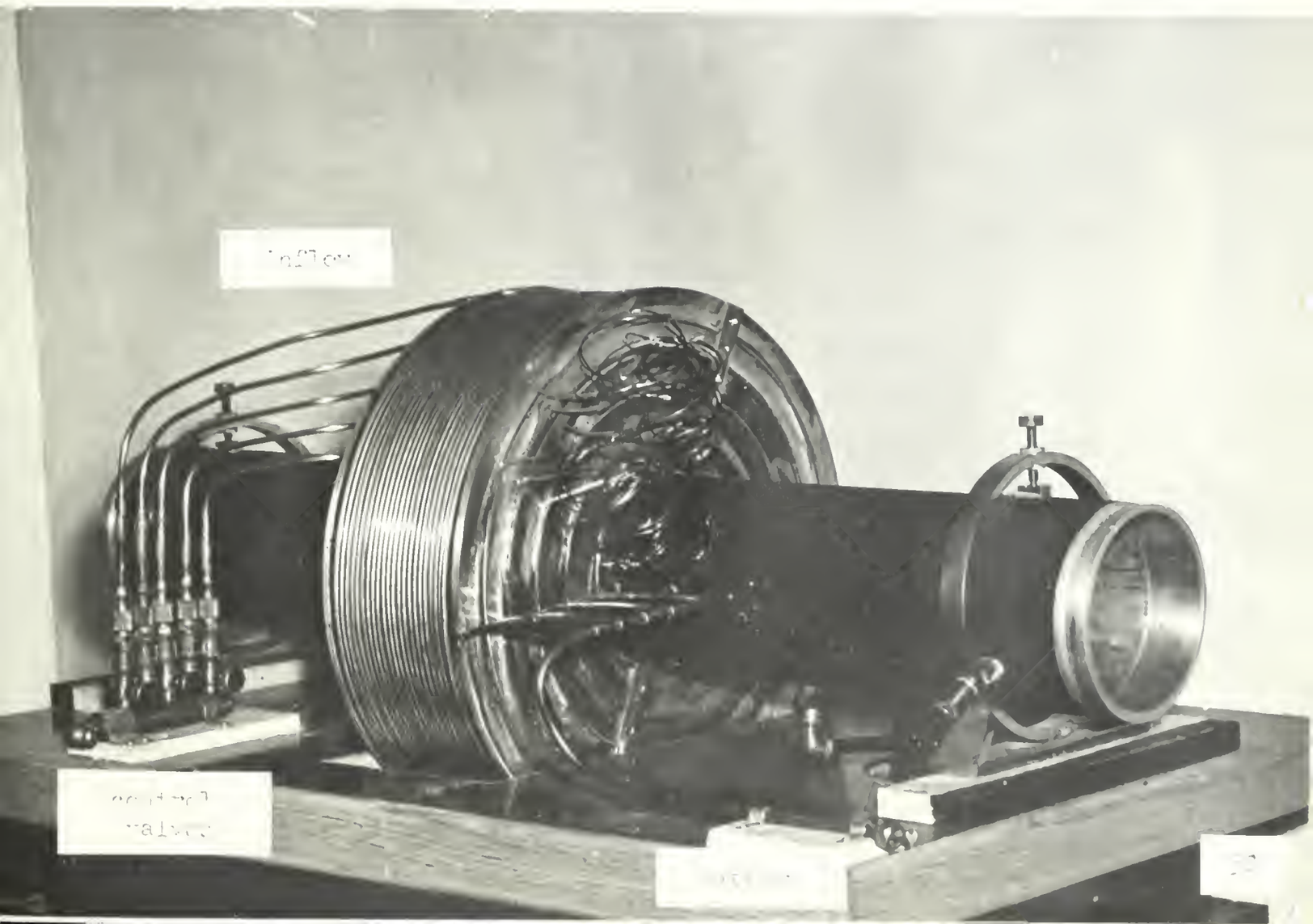


Figure 16. COOLING SYSTEM, BET SPECTROMETER, NEW COIL (U[illegible])





[illegible] SPECTROMETER, NEW COIL (U.N.S.)

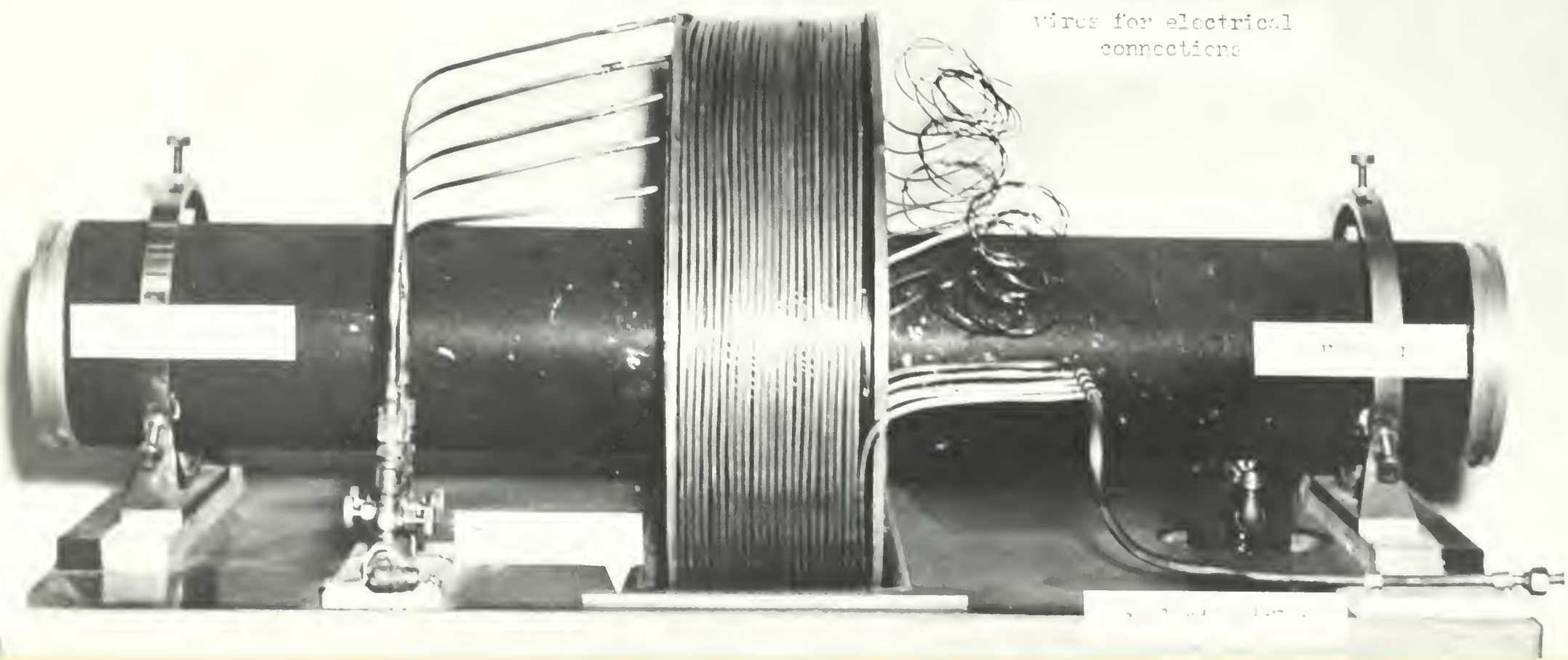


Figure 18. SOURCE END, BE[illegible] SPECTR[illegible], [illegible] COIL ([illegible])

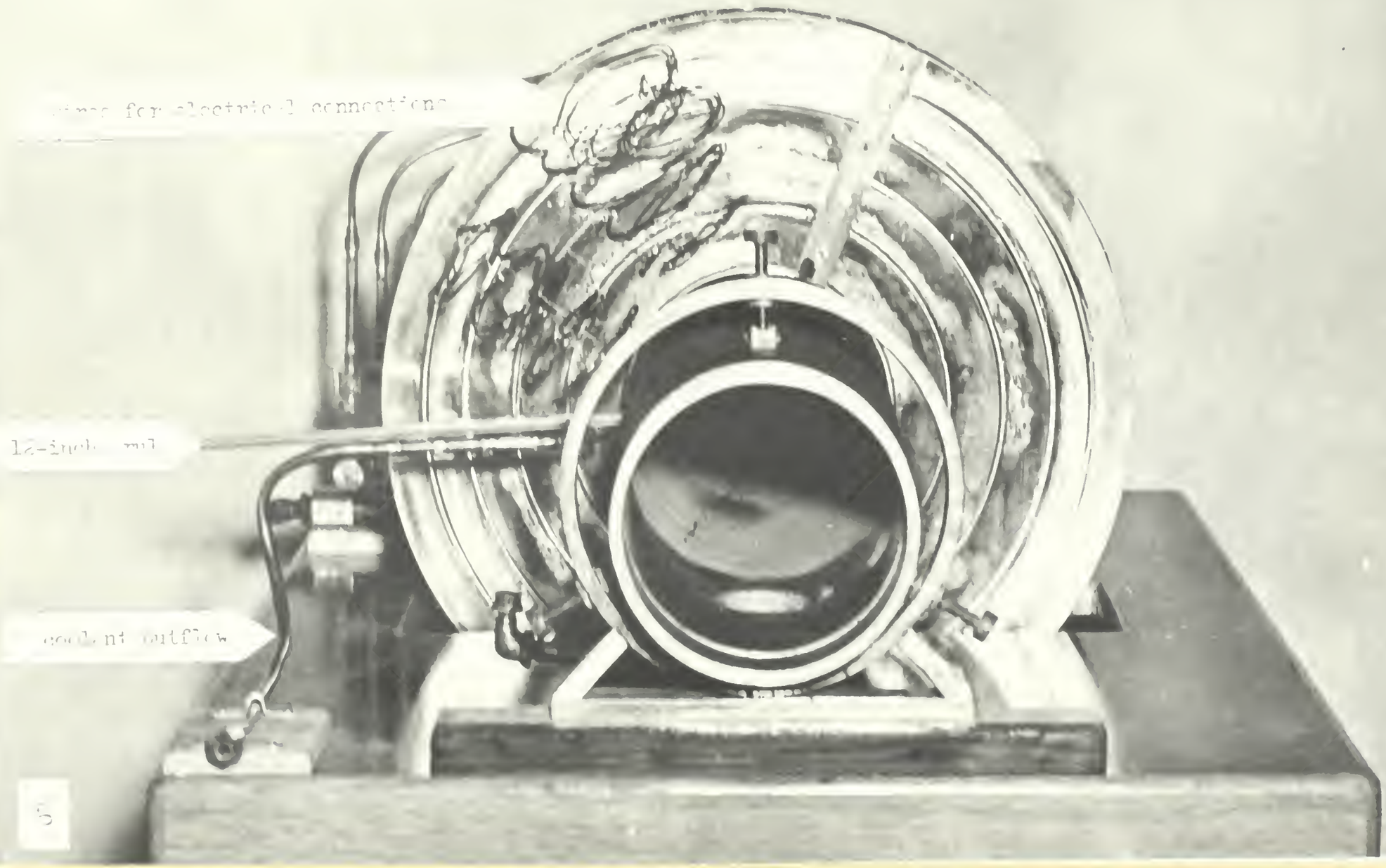
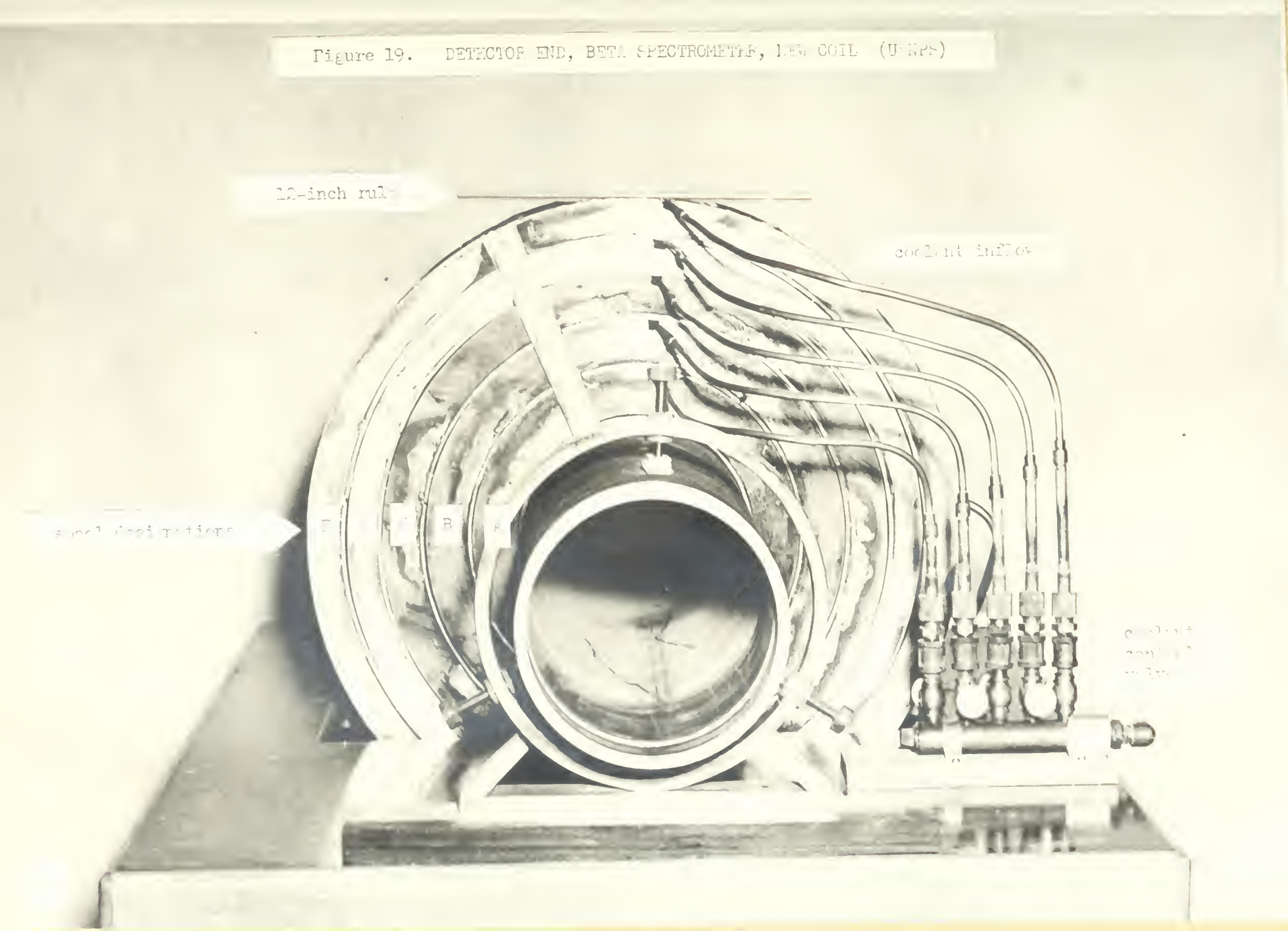


Figure 19. DETECTOR END, BETA SPECTROMETER, NEW COIL (U-NPS)



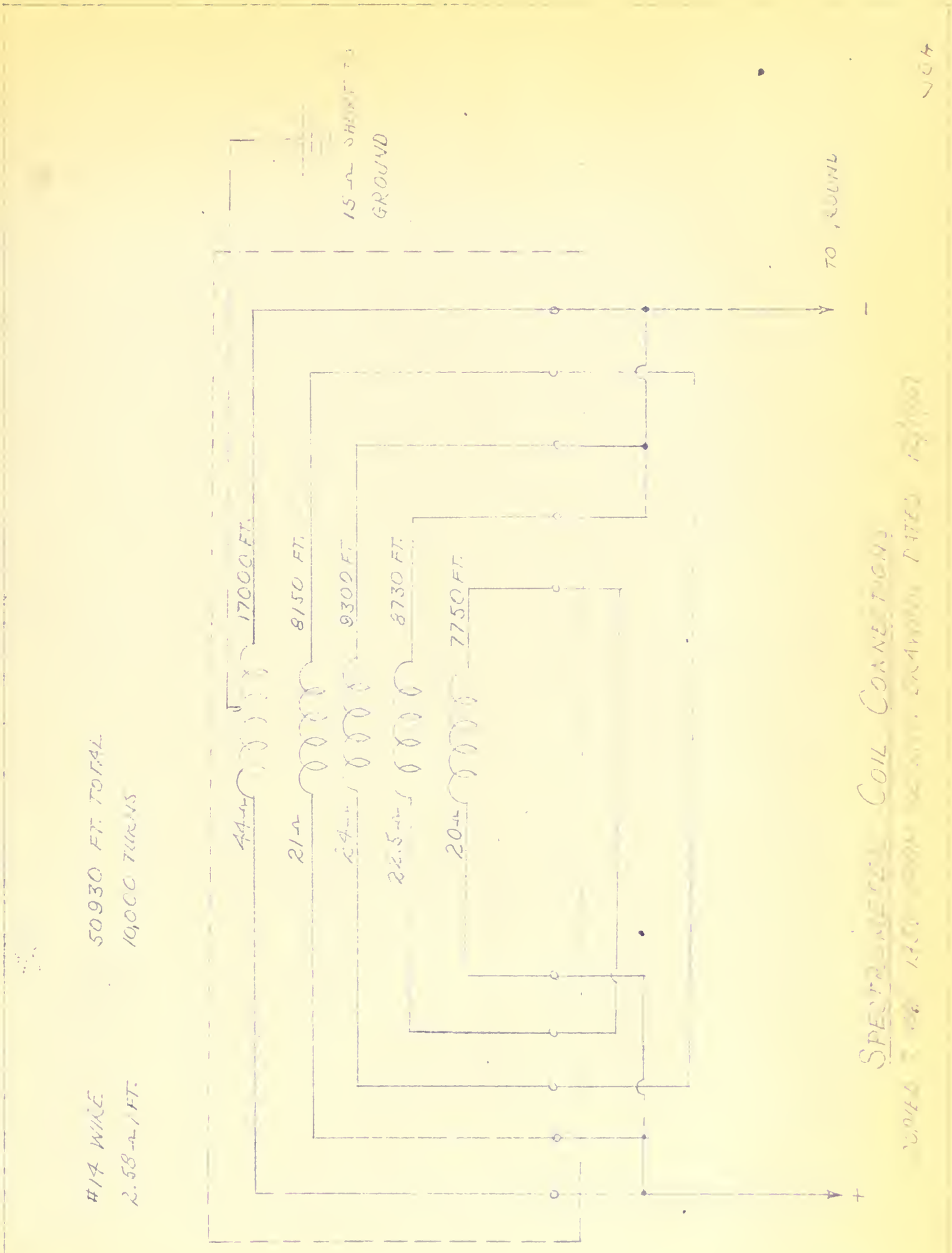
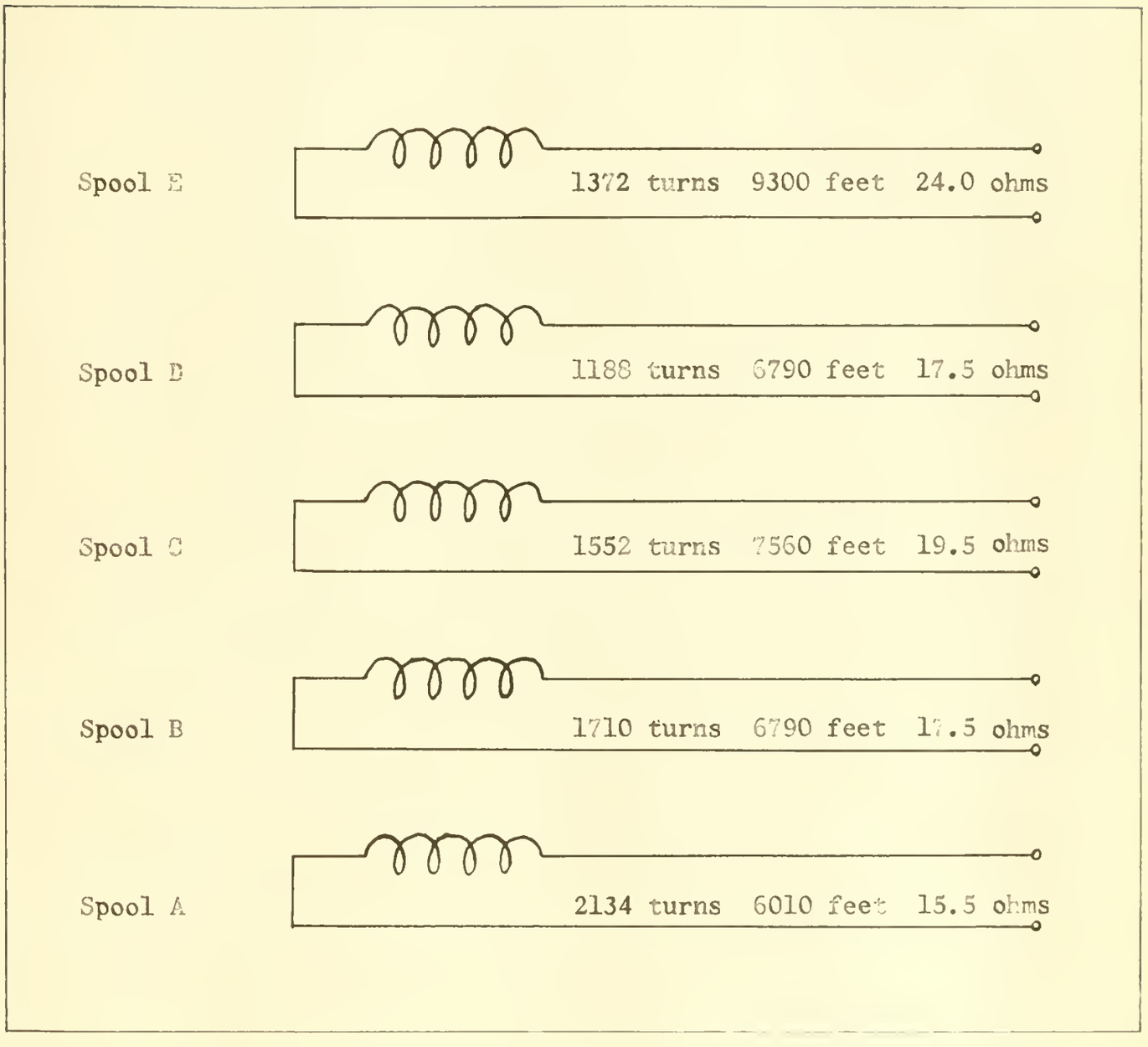


Figure 20. ELECTRICAL DIMENSIONS, ORIGINAL COIL, BETA SPECTROMETER (USNPS)



#14 wire, nominal resistance 2.58 ohms/1000 feet at 25°C.
Total length of wire: 36,450 feet.
Total resistance: 94.0 ohms.
Total turns: 7956.

Figure 21. ELECTRICAL DIMENSIONS, NEW COIL, LRT. SPECTROMETER (USMTS)

magnetic field by experimental methods was not practical. It appears that the best method for determining the shape of the field is to compare it with a known field of a similar type of thin-lens spectrometer with comparable dimensions.

Figure 22, page 45, shows the general assembly of the main tube and magnetic coil of the USNPS spectrometer; only the principal dimensions have been indicated. Fortunately there exists a thin-lens spectrometer of similar geometry at Iowa State College, and for which much information regarding the magnetic field and electron trajectories has been published by J. M. Keller, et al [32]. Also K. Siegbahn [56] has discussed the magnetic field of a thin-lens magnet of slightly different dimensions. Figure 23, page 46, shows the dimensions of the USNPS spectrometer as compared with those of the thin-lens spectrometers of Iowa State College and Siegbahn. Figure 24, page 47, represents the magnetic field distribution of the thin-lens according to Siegbahn. In general, the same shape of field would apply for the USNPS magnet coil, with the modification as indicated in the abscissa scale.

For a coil of rectangular cross-section of axial length t, inner and outer radii a_1 and a_2, and n turns, the axial field per ampere of magnetizing current is given by [42]:

$$H_0(z) = \frac{2\,n\,\pi}{10\,t\,(a_2 - a_1)}\,[B\,(a_2) - B\,(a_1)]$$

where $B\,(a) = (z + \frac{t}{2})\,\ln\left\{a + \left[a^2 + (z + \frac{t}{2})^2\right]^{1/2}\right\}$

$$- (z - \frac{t}{2})\,\ln\left\{a + \left[a^2 + (z - \frac{t}{2})^2\right]^{1/2}\right\}.$$

50 CM OR 19.68" (DATUM)

50 CM OR 19.68" (DA

DETECTOR TUBE ASSEMBLY

7" I.D. (NOMINAL)

SHIELDED CABLE TO PULSE COUNTER

TUBE

WATER COOLED MAGNET COIL

LEGEND

- LEAD
- ALUMINUM
- BRASS OR BRONZE
- LUCITE
- COIL WINDINGS

NOTES:

1. ALL PARTS EXCEPT G.M. TUBES, PHOTOMULTIPLIER TUBE & MU-METAL SHIELD ARE NON-MAGNETIC
2. THE AXIS OF THE BETA SPECTROMETER IS SET LEVEL, AND ORIENTED IN A NORTH-SOUTH DIRECTION.
3. THE VERTICAL COMPONENT OF THE EARTH'S MAGNETIC FIELD IS COMPENSATED FOR BY MEANS OF LARGE HORIZONTAL MAGNET COILS PLACED APPROXIMATELY 3 FT. ABOVE & BELOW SPECTROMETER.
4. LUCITE BAFFLES ARE PAINTED WITH AQUADAG & SEALED TO THE VACUUM TUBE WITH AQUADAG

50 CM OR 19.68" (DATUM)
50 CM. OR
DETECTOR TUBE ASSEMBLY
SHIELDED CABLE TO PULSE COUNTER
TUBE
WATER COOLED MAGNET COIL
2 Kev ≈ 10^3 gauss
√E/ρ = const 20 ev = 100 gauss
2,000
Longway
Roger Dyer
#30+11

50 CM. OR 19.68" (DATUM)

7" I.D. (NOMINAL)

SOURCE TUBE

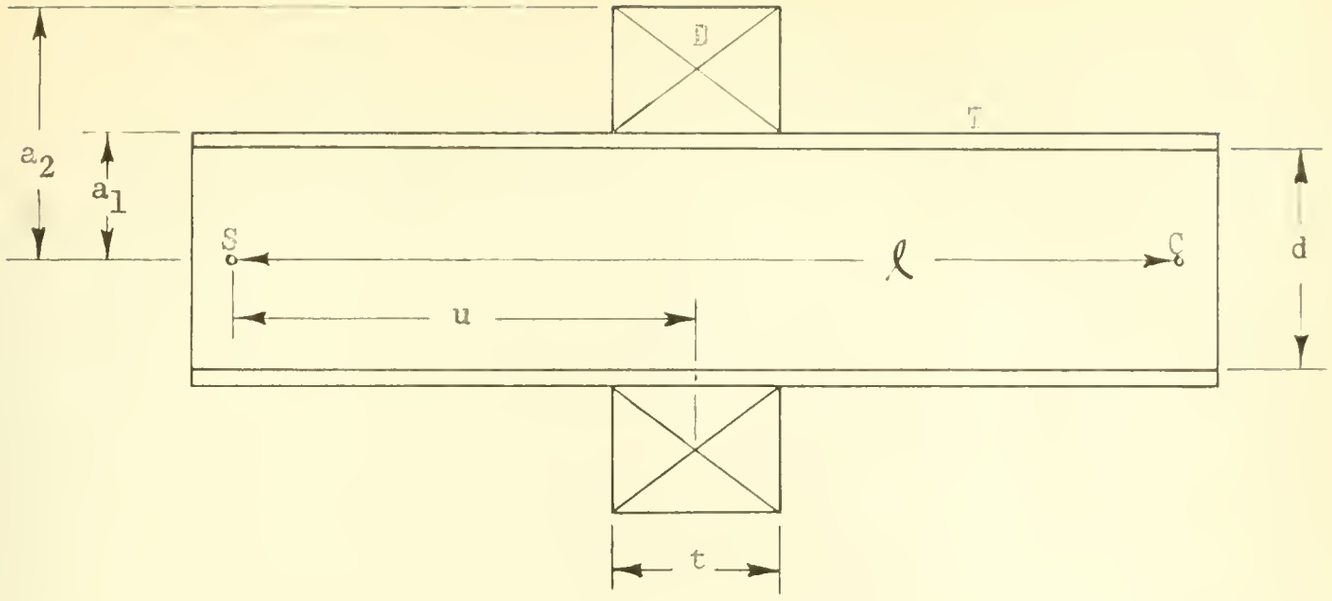
WATER COOLED MAGNET COIL

TO DIFFUSION PUMP AND
MECHANICAL VACUUM PUMP

U.S. NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

GENERAL ASSEMBLY
BETA SPECTROMETER

COPIED BY	MARCH 5, 1956	APPROVED:
J.O. HUTTON	SCALE $\frac{1}{2}$" = 1"	FGR



a_1 - Inside radius of coil
a_2 - Outside radius of coil
d - Inside diameter of main tube
ℓ - Distance from source to counter
u - Distance from source to center of coil

t - Thickness of coil
C - Counter
D - Coil
S - Source
T - Main Tube

ITEM	USNDS	IOWA S.C.	SIEGBAHN
ℓ	100.00	100.00	
u	50.00	50.00	
t	15.88	10.00	15.00
a_1	10.17	9.90	7.50
a_2	27.30	28.30	22.50
d	17.78	17.14	

Note: All dimensions are in centimeters.

Figure 23. COMPARISON OF THIN LENS BETA SPECTROMETERS

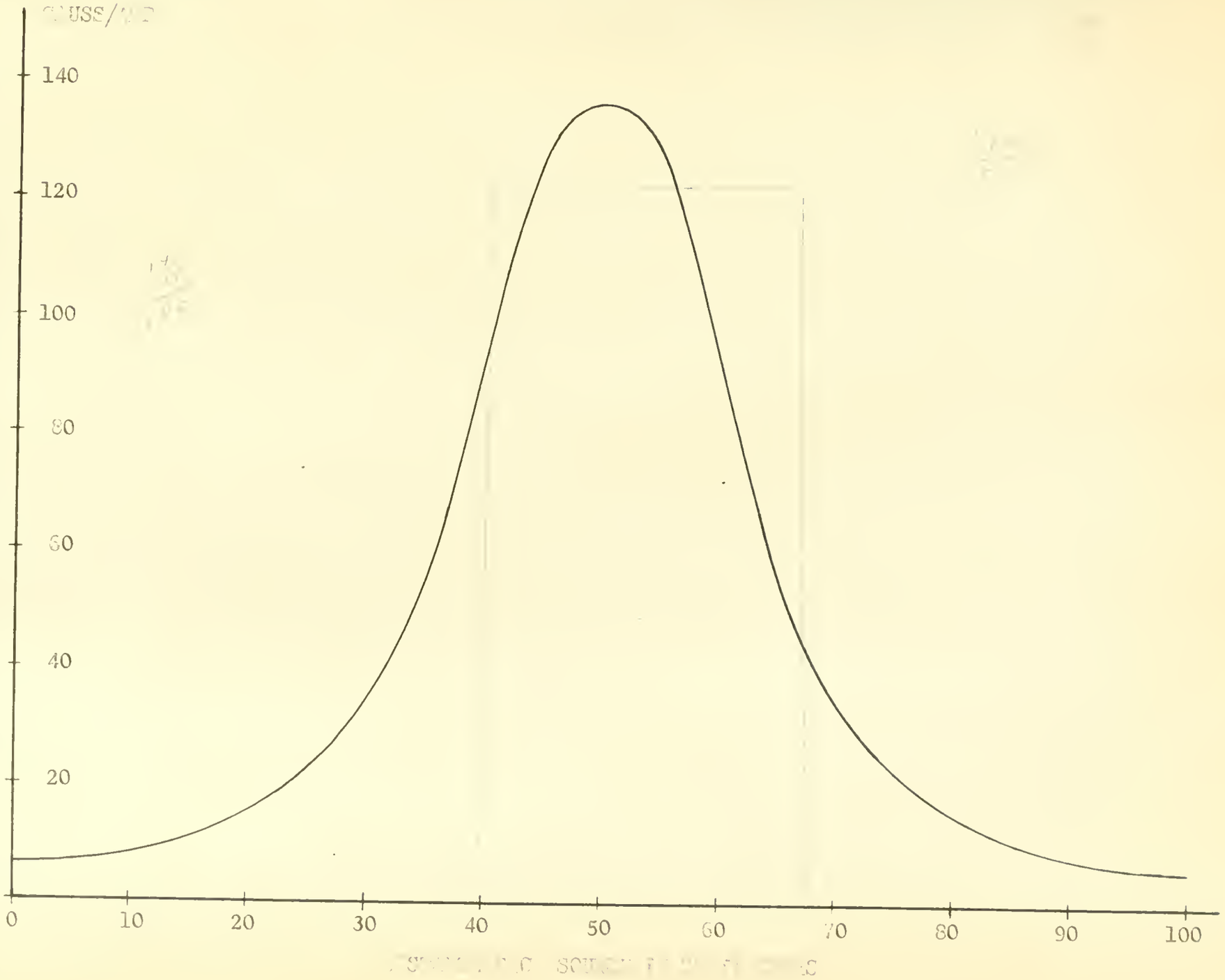


Figure 24.

Using values of a_1 = 10.17 cm, a_2 = 27.30 cm, t = 15.88 cm, and n = 7956, the value of the magnetic field at the midpoint of the axis of the USNPS coil, i.e., at z = 50 cm, is 14.7 gauss per ampere. With a current of about 9.0 to 9.5 amperes, the magnetic field at the center of the USNPS coil would approximate 135-140 gauss, and the values of the field at other points would approximate those of the curve of Figure 24, page 47.

In using the above values of a_1 and a_2, it is recognized that the above equation only approximates the true field intensity. The winding is interrupted four times by the cooling coils and the layer of metal forming the spindle of each succeeding spool. The effect of these coils and spindles is to make the field at the center of the lens stronger than the value calculated above, and to reduce the field below the calculated value at distances greater than about 15 cm from the center [32].

6. Electron Trajectories in the Thin-lens Magnetic Field.

In beta-ray spectroscopy it has been found convenient to express the momentum of an electron by means of its "Hρ" value, where H is the intensity of the magnetic field and "ρ" is the radius of curvature, which is inversely proportional to the axial magnetic field strength [33]. The use of momentum coordinates instead of energy ones in beta-ray spectroscopy is partly due to the simple fact that it is the momentum of the focused electrons and not the energy which is proportional to the magnetic field of the spectrometer or to the current.

A single equation for an electron trajectory can be derived from the equations of motion for an electron in a cylindrically symmetric magnetic

field with no azimuthal component [8, 9, 22]. The magnetic field is described by a vector potential which is always in an azimuthal direction. Time and the azimuthal variable can be eliminated by means of the two motion constants, energy and angular momentum. Since we will consider only the case of a point source, every particle will start from the axis, hence the angular momentum is zero, and the resulting equation for the trajectory [38, 65], or radial displacement of r as a function of axial displacement z, is:

$$r''(k^2-A^2)/\left[1+(r')^2\right] - r'A\left(\partial A/\partial z\right) + A\left(\partial A/\partial r\right) = 0,$$

where A is the vector potential per unit magnetizing current, and k is the electron momentum in "Hρ" units, also divided by the magnetizing current. Primes indicate differentiation with respect to z.

The magnetic field H_o is calculated along the axis according to the equation given in sub-paragraph five above. Using H_o so calculated, the vector potential at any point (r, z) is calculated [17] by the expansion:

$$A(r,z) = \frac{r}{2}H_o(z) - \frac{r^3}{16}\left(\frac{\partial}{\partial z}\right)^2 H_o(z) + \frac{r^5}{384}\left(\frac{\partial}{\partial z}\right)^4 H_o(z)$$

$$+ \text{-----} + \frac{(-1)^n}{n!(n+1)!}\left(\frac{r}{2}\right)^{2n+1}\left(\frac{\partial}{\partial z}\right)^{2n} H_o(z) + \text{-----}.$$

The value of "A" has been calculated by J. M. Keller, et al [32], using the first three terms of this expansion, resulting in trajectories for electrons of a given momentum as shown in Figure 25, page 50, for the Iowa State College spectrometer.

Since the magnetic field of the new thin-lens coil of the USNPS spectrometer is not yet known, it appears that the best method of

Figure 25.

determining the electron trajectories (traces) is again by means of comparison with those of a spectrometer of similar geometry. For this purpose the thin-lens spectrometer of Iowa State College seems to offer the best comparison [32], and its curves have been adapted to the USNPS spectrometer without modification. The close similarity of the geometry of the two spectrometers, as shown in Figure 23, page 46, appears to permit this adaptation without the introduction of any serious error.

7. Other Characteristics of the USNPS Spectrometer With New Magnet Coil.

As mentioned in Chapter II, Deutsch et al developed a simplified theory of the short lens (thin-lens) spectrometer with circular exit window. See Figure 7, page 27, for clarification of the notations used here. This simplified theory requires exit slit E to be removed, and counter window W to act as the exit slit.

Let u be the distance from the source to the symmetry plane of the lens, and ℓ be the distance from source to exit window. Then the magnification of the lens $M = (\ell - u)/u$. Let s be the source radius, w the exit window radius, r_1 and r_2 the internal and external radii of the entrance slit. Neglecting spherical aberration, the highest peak-intensity for a given resolving power occurs when $r_2/r_1 = \sqrt{2}$ and the window is as large as the source image, i.e., when $w = Ms$. At highest peak-intensity the base spread η_o is given by

$$\eta_o = 2.42 \frac{M}{M+1}\left(\frac{s}{r_2}\right)$$

and the luminosity L by

$$L = 0.54\,(M+1)^2\, s^2 r_2^2/\ell^2 \qquad \text{or} \qquad L = 0.092 \frac{(M+1)^4}{M^2}\left(\frac{r_2^4}{\ell^2}\right)\eta_o .$$

If we substitute in these formulas, the average emission angle

$\alpha \doteq r_2/u$ (assumed $\ll 1$), we get

$$\eta_o = 3.3\, M \alpha^{-2} \left(L/\ell^2\right)^{1/2}.$$

For a given α, it is then apparent that the magnification M must be made as small as conveniently possible if the base spread is to be minimized. However, if the activity of the available source is great enough so that a loss of luminosity is no objection, Persico and Geoffrion recommend making M = 1, since this symmetrical arrangement minimizes some of the causes of spread, such as inaccuracy of alignment, aberrations, and stray magnetic fields [42]. It will be noted from Figure 22, page 45, or Figure 23, page 46, that the magnification M of the USNPS spectrometer is M = 1.

In order to calculate the theoretical resolving power one must know the spherical aberration of the system. This can be found by ray-tracing, either by mathematical means if the field distribution is known, or experimentally: the latter method yields more accurate results [56].

In order to get an estimate of the resolving power P, one can neglect the spherical aberration. The geometry alone will then yield a spread

$$\eta = \frac{Ms + uw}{(M+1)\, 2r_1}.$$

For a magnification M = 1, $\eta = \frac{s + uw}{4r_1}$.

By definition the resolving power $P = 1/\eta$, or $P = \frac{4r_1}{s + w}$.

In the USNPS spectrometer, r_1 = 5.2 cm, r_2 = 7.7 cm, and estimating that s $\doteq$ 0.2 cm and w $\doteq$ 0.6 cm, the base spread η_o = 0.0314, the luminosity L = 0.000512 cm^2, and the resolving power P = 26.0.

8. Alignment of Axes.

In order to insure that the axes of the various baffles coincide in direction and in position with the symmetry axis of the magnetic field, in all short lens spectrometers the baffles, the source and the counter are rigidly fixed to the walls of the vacuum chamber. To get proper alignment this entire rigid unit can be displaced slightly with respect to the coil by means of leveling screws. This adjustment is very critical and can be made by trial and error, or by a method described by N. F. Verster [65].

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APPENDIX I

DATA FOR NEW COIL

ITEM	SPOOL A	SPOOL B	SPOOL C	SPOOL D	SPOOL E	TOTAL
1. Number of layers of winding	22	18	16	12	14	82
2. Average number of turns per layer*	97	95	97	99	98	
3. Total number of turns on spool (item 1 x item 2)	2134	1710	1552	1188	1372	7956
4. Measured resistance (ohms)	15.5	17.5	19.5	17.5	24.0	94.0
5. Length of wire (ft) (item 4 x 1000/2.58)**	6010	6790	7560	6790	9300	36,450
6. Inside diameter of spool (inches)	7.750	11.155	14.300	17.250	19.750	7.750
7. Inside diameter of winding (inches)	8.000	11.400	14.550	17.500	20.000	8.000
8. Outside diameter of spool (inches)	11.140	14.285	17.235	19.735	22.250	22.250

*Based on actual count of several random layers.

**Based on nominal resistance for #14 wire of 2.58 ohms/1000 ft at 25° C.

Note: Nominal weight of #14 wire is 12.4 lb/1000 ft.

APPENDIX II

DEFINITIONS AND NOTATIONS

(Adopted from Persico and Geoffrion [42])

Spectrograph: an instrument recording the β-ray energy spectrum on a photographic emulsion.

Spectrometer: an instrument measuring the relative number of β-particles in a short energy range, which can be gradually displaced along the spectrum.

Spectroscope: spectrograph or spectrometer.

Flat spectroscope: a spectroscope in which the central electron path lies in a plane (which will be considered as a horizontal plane).

Helical spectroscope: a spectroscope in which all of the paths of the particles are essentially of helicoidal shape. It is usually a spectrometer and can be a solenoidal, long lens, or short lens type.

Baffles: all the obstacles intended to prevent electrons or gamma-rays from reaching the detector directly or by scattering. Among these are the first diaphragm determining the entrance slit and the second diaphragm, determining the exit slit (in spectrometers). Both the entrance and the exit slit may have their two edges in different planes. Still other baffles act as shields against scattered radiation without contributing to the determination of the direct beam.

Momentum (p): the "quantity of motion" or "mechanical momentum" of an electron: $p = m_v v$, where v is the velocity and m_v the relativistic mass.

In all formulas concerned with the magnetic deflection of electrons the momentum appears divided by the electron charge in e.m. units: this ratio will be denoted by p*:

$$p^* = p/e_m.$$

This quantity is called by many authors "the $H\rho$ of the electron" even when there is no explicit reference to H and ρ (and even when $H = 0$ and $\rho = \infty$). Its dimensions are gauss-cm.

Total activity: The number of electrons emitted by a source in all directions per unit time.

Specific activity: The total activity of a source divided by its area.

Intensity: The number of electrons reaching the counter of a spectrometer per unit time (apart from scattered radiation) with a given source and a given magnetic field.

Transmission (T): The intensity (see above) divided by the total activity of the source. Also: the fraction of all emitted electrons reaching the counter (except by scattering) with a given source and a given magnetic field.

Line profile: In a spectrometer, it is the diagram obtained, with a monokinetic source, by measuring the transmission (see above) with different values of the coils current j, and plotting it against the values of p* which correspond to those of j according to the calibration law. In a spectrograph, it is the diagram having as ordinate the number of electrons falling per unit time and unit area at a point of the plate, with a monokinetic source of unit total activity, and as abscissa the value of p* corresponding to that point of the plate according to the calibration law.

Half-maximum width (Δp^*): The width of the line profile at half-maximum ordinate.

Spread (η): The relative half-maximum width:

$$\eta = \Delta p^*/p^* = \Delta p/p.$$

The spread is usually expressed in percent and is called by different authors: "irresolution," "spread," "resolving power," "inverse resolving power," "limit of resolution," "inverse momentum resolution," "half-intensity width." Some authors call "resolving power," the quantity $\Delta E/E$, where E is the energy and ΔE is the half-maximum width of the line profile in the scale of energies.

Resolving Power (P): The inverse of the spread:

$$P = 1/\eta = p^*/\Delta p^* = p/\Delta p.$$

This definition conforms to current usage in optics.

Base width ($\Delta_o p^*$): The width of the line profile at zero ordinate. Also called: "total width."

Base spread (η_o): $\eta_o = \Delta_o p^*/p^* = \Delta_o p/p.$

Base resolving power (P_o): $P_o = 1/\eta_o = p^*/\Delta_o p^* = p/\Delta_o p$

Dispersion: In the plane of the photographic plate, or of the exit slit, let us call x the distance between an arbitrary origin and the line where electrons of momentum $p = e_m p^*$ from a point source are focused. Then $\gamma = dx/dp^*$ will be called "dispersion." Clearly, if the real image (or the ring image) of the source has a width Δx (due to the source width and to aberration) and if the width of the exit slit is X, the base width of the line profile will be approximately $\Delta_o p^* = (X + \Delta x)/\gamma$.

Solid angle (Ω): The solid angle filled by the initial directions of all the electrons of a monokinetic source leaving the center of the

source (or, practically, any point of it) and passing through the entrance slit. It is also called "angle of collection."

Gathering power (ω): The fraction of all the emitted electrons of a monokinetic source passing through the entrance slit. For a source emitting isotropically it is given by

$$\omega = \Omega/(4\pi).$$

The gathering power is usually expressed in percent. In a spectrometer it is equal to the maximum intensity obtainable, with an exit slit wide open, with a source of unit total activity; so, it can be said that the gathering power measures the ability of the instrument to deal with sources of very low total activity.

Over-all gathering power: In a spectrometer the gathering power ω characterizes only the parts of the instrument up to the exit slit. The over-all gathering power with a given setting of the exit slit is measured by the value T_{max} of the transmission at the peak of the line profile. Clearly, $T_{max} \leq \omega$.

Luminosity (L): The gathering power multiplied by the source area: $L = \omega\sigma$. In a spectrometer, it is equal to the maximum intensity obtainable, with an exit slit wide open, with a source of unit specific activity (and of the given area). It measures therefore the ability of the instrument to deal with sources of very low specific activity. It will be express in cm^2.

Over-all luminosity (L*): In a spectrometer, the luminosity characterizes only the parts of the instrument up to the exit slit. The over-all luminosity L* with a given setting of the exit slit is measured

by the peak transmission T_{max} multiplied by the source area:

$$L^* = T_{max}\,\sigma.$$

Clearly, $L^* \leq L$.

Efficiency μ: The ratio of the luminosity L of a flat spectroscope to its useful pole piece area $\sum$. This dimensionless quantity helps the comparison between instruments of different types, by reducing them effectively to the same size.

APPENDIX III

FUNDAMENTAL FORMULAS

(Adopted from Persico and Geoffrion [42])

Some of the formulas of relativistic mechanics that are basic in the theory of beta-ray spectroscopes are given below:

If m is the rest mass of the electron, m_v its mass at speed v and p its momentum, then

$$p = m_v v = m (1 - v^2/c^2)^{-1/2} v. \tag{1}$$

Since the magnetic deflection does not alter v, the relativistic change of mass does not introduce any complication in the movement of a given electron, provided the right value of m_v is taken at the start.

The radius of curvature ρ of the path of an electron moving at right angles to a magnetic field H is given by the well-known formula

$$H\rho = p/e_m, \tag{2}$$

where e_m is the electron charge in absolute e.m.u. ($e_m = 1.60199 \times 10^{-20}$). This formula suggests taking as a measure of momentum the quantity

$$p^* = p/e_m = H\rho \tag{3}$$

which will be expressed in gauss-cm (or "gilberts").

Let E be the kinetic energy (usually expressed in Mev). Its relation to p^* is most conveniently expressed by introducing the two universal constants

$$E_o = mc^2 = 0.5107 \text{ Mev},$$

$$p_o^* = mc/e_m = 8.125 \times 10^{-7} \text{ gilbert}.$$

Then the relation is

$$(E/E_o + 1)^2 - (p^*/p_o^*)^2 = 1. \tag{4}$$

The relation between E in Mev and p* in gilberts is tabulated, for instance, in "Miscellaneous Physical Tables" (National Bureau of Standards, 1941).

The "spread" of an instrument (or its inverse, the resolving power), is most easily calculated in terms of momentum, but sometimes it is needed in terms of energy. To pass from the one to the other the following formula, obtained by differentiation of (4), is useful:

$$\eta = \frac{dp^*}{p^*} = \frac{dp}{p} = \frac{E + E_o}{E + 2E_o} \frac{dE}{E}. \qquad (5)$$

It is to be noted that in the theory of magnetic spectroscopes all the relativistic corrections can be ignored as far as the spectrum is studied in terms of p (or p*) rather than of E.

APPENDIX IV

USEFUL REFERENCES FOR FURTHER STUDY OF BETA-RAY SPECTROMETERS

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